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NAVAL SHIP CONCEPT DESIGN FOR THE REPUBLIC OF KOREA NAVY: A SYSTEMS ENGINEERING APPROACH

by

Hanwool Choi

September 2009

Thesis Co-Advisors: Clifford Whitcomb
Fotis Papoulias

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13. ABSTRACT (maximum 200 words)

This thesis presents a new systems engineering based approach to naval ship concept design for the Republic of Korea (R.O.K.) Navy. The R.O.K. Navy currently uses a traditional naval architecture approach in concept design. Naval architects focus only on naval architecture issues such as speed, range, and displacement; combat systems engineers focus on the performance of combat systems, weapons, and sensors. This design process creates some integration problems in the late design stage and during construction. For this reason, there is a growing interest in the systems engineering approach design concept in the R.O.K. Navy.

Naval ship design is an aggregate of engineering, computer science, management, and even strategy and policy. Naval ship engineers should consider not only naval architecture issues such as hull form, stability, structure, maneuverability and propulsion, but also mission needs, effectiveness, cost/risk benefits, and integration with all combat systems. Naval architecture and combat systems engineering are a part of the design process, and they must be considered simultaneously a systems engineering approach to combatant ship design. To properly design a naval ship, engineers should consider how each of the systems combines optimally into a system of systems.

The resulting process focuses on the systems engineering process applied to naval combatant design. Two systems engineering based naval ship concept design processes, one from NATO and the other from the U.S. Navy's Total Ship Systems Engineering (TSSE) program at the Naval Postgraduate School (NPS), are presented. The difference between the concept design process in the R.O.K Navy and the TSSE processes is studied. Based on the above studies and comparison of the processes, a new concept design process is proposed for the R.O.K. Navy. Finally, the Future Frigate (FFX) case study is performed using the newly proposed concept design process.

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NAVAL SHIP CONCEPT DESIGN FOR THE REPUBLIC OF KOREA NAVY: A SYSTEMS ENGINEERING APPROACH

Hanwool Choi
Lieutenant, Republic of Korea Navy
B.A., Republic of Korea Naval Academy, 2004

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Author: Hanwool Choi

Approved by: Clifford Whitcomb
Thesis Co-Advisor

Fotis Papoulias
Co-Advisor

David Olwell
Chairman, Department of Systems Engineering

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I. INTRODUCTION

A. BACKGROUND OF STUDY

Naval combatant ship design is an aggregate of naval architecture, marine engineering, computer science, management, and even strategy and policy. Naval ship engineers should consider not only naval architecture issues such as hull form, stability, structure, maneuverability and propulsion, but also mission needs, effectiveness, cost/risk benefits, and integration of all combat systems. Naval architecture and combat systems engineering are critical parts of the design process, and they must be considered simultaneously. A total ship systems engineering approach to design informs decision makers about the optimal effectiveness and cost trade-offs from the infinite combinations that meet the desired requirements.

In the Republic of Korea (R.O.K.) Navy, naval ship concept design is still mainly done using a traditional naval architecture “design spiral” method. Naval architects focus only on naval architecture issues such as speed, range, and displacement. However, combat systems engineers focus on the performance of combat systems, weapons, and sensors. This separate design emphasis not only creates some integration problems but also sets the stage for potential design changes during the late design stages, in order to meet the operational needs. For these reasons, there is a growing interest in implementing systems engineering approach to combatant concept design in the R.O.K. Navy.

Naval shipbuilding industries and research institutes now attach no small importance to systems engineering as applied to design and shipbuilding because cost reduction and improved suitability are expected outcomes when a systems engineering process is implemented in design and production in the R.O.K.

Some universities are building systems engineering into the curriculum of naval architecture and ocean engineering departments to foster the development of ship systems engineering specialists. In this recent trend, the R.O.K. Navy’s systems engineering design approach will give a positive impulse to the field of naval engineering in Republic

of Korea. In order to keep the R.O.K. Navy on the leading edge of technology, a systems engineering design process must be used in the early stage of ship concept design.

B. PURPOSE OF STUDY AND RESEARCH QUESTIONS

The purpose of this study is to present a new concept design process for the R.O.K. Navy in terms of a systems engineering approach.

Primary Research Questions

- How can systems engineering be applied to naval ship concept design in the R.O.K. Navy?

Secondary Research Questions

- Why is a systems engineering approach needed in naval ship design?
- What problems arise from the R.O.K. Navy's current concept design process, and can a systems engineering approach provide a solution for these problems?
- How does the R.O.K. Navy's concept design process differ from the U.S. Navy's Total Ship Systems Engineering (TSSE) concept design process?
- Are there any constraints or assumptions for applying the U.S. Navy's TSSE concept design process to the R.O.K. Navy?
- What infrastructure is needed to apply systems engineering in the R.O.K. naval ship concept design process with respect to design?

C. BENEFITS OF STUDY

This new concept design process studied is expected to draw the R.O.K. Navy's attention to the need for systems engineering in naval ship design. It should open a new phase of concept design methods for the R.O.K. naval ship engineering center. This thesis will also provide a guide for the next generation naval ship concept design in the R.O.K. Navy.

D. SCOPE

This thesis is focused on the early stage of ship design, because the Korean Navy has a duty to provide a well balanced concept design for its proposed ships before preliminary and detailed designs which are accomplished by the shipyard. Moreover, a ship's general characteristics and capabilities are usually determined in the concept design stage, so it is essential to set up a well-established concept design process for a good final outcome.

Chapter II presents a systems engineering overview and the trends of systems engineering applied naval ship design processes. Chapter III focuses on a comparison of the current concept design process between the R.O.K Navy and the U.S. Navy's TSSE. Through comparison of those two concept design processes, an appropriate new R.O.K naval ship concept design process is explained. Chapter IV will show the Future Frigate (FFX) case study, applying the newly-proposed concept design process. Finally, Chapter V presents the conclusion, recommendations, and identifies area for further research.

E. METHODOLOGY

The study is performed based on a generic U.S. Navy concept design process which uses systems engineering. Through the comparison between the two countries' concept design processes, concept design process which addresses the R.O.K. Navy's need is presented. After developing the concept design process, the different design outcomes are shown using a case study on the Future Frigate (FFX) which is currently being built at a Korean naval shipyard.

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II. SYSTEMS ENGINEERING APPLIED DESIGN OVERVIEW

A. A BRIEF OVERVIEW OF NAVAL COMBATANT SHIP DESIGN AND SYSTEMS ENGINEERING

1. What is Naval Combatant Ship Design?

Naval combatant ship (warship) design is an inherently complex process as compared to a typical commercial ship design. The naval combatant ship design complexity has been described as follows:

> Complexity is significantly increased when the particular ship being designed is a naval surface combatant (warship). In this case, the designer must only not address the factors common to all seagoing vessels such as hull form, propulsion, and maneuverability, but the choice and placement of sophisticated weapons systems and sensors must also be considered. (Szatkowski, 2000)
>
> The complexity associated with the engineering of warship concepts is observed when considering the multiplicity of functions desired and the large number of physical subsystems and parts. The fact that the system must be considered becomes obvious if one considers that inserting a single highly advanced warship as a node into and existing battlegroup, that interoperability cannot be obtained since the equipment processing and interconnective protocols are incompatible. (Whitcomb & Szatkowski, 2000)

Those complexities can be considered using a systems engineering approach. Systems engineering must be implemented due to the need for integration of complex systems and different perspectives such as naval architecture and combat systems.

2. What is Systems Engineering?

Many organizations provide definitions of systems engineering as follows:

- Systems engineering is commonly defined as *an interdisciplinary approach and means* to enable the realization of successful systems. (INCOSE Web site)
- Systems engineering is *a robust approach* to the design, creation, and operation of systems. (NASA Systems Engineering Handbook, 1995)

- Systems engineering consists of two significant disciplines: the technical knowledge domain in which the systems engineer operates, and systems engineering management. (DoD Systems Management College, Systems Engineering Fundamentals, 2001)
- Systems engineering is the set of overarching processes that a program team applies to develop an operationally effective and suitable system from a stated capability need. Systems engineering processes apply across the acquisition life cycle (adapted to each phase) and serve as a mechanism for integrating capability needs, design considerations, design constraints, and risk, as well as limitations imposed by technology, budget, and schedule. (DoD, Defense Acquisition Guidebook, 2008)

In summary, these organizations tend to view SE as a process rather than a discipline. They all have a common theme: engineering and management. Based on these definitions, systems engineering is an interdisciplinary engineering management process which enables the realization of successful systems that meets the user’s needs. Systems engineering is a broad topic that includes hardware, software, and human systems. It transforms operational capabilities into an integrated system design through concurrent considerations of all life cycle needs with the most cost-effective methods in terms of performance, cost, and schedules. The systems engineering processes should be applied during concept definition and then continuously throughout the life cycle of a project.

3. Systems Engineering Process in Naval Ship Design

The IEEE standard 1220–1998 describes an operational architecture as a “Problem Space” as shown in Figure 1. The problem space should be defined and well understood in terms of an operational view in order to begin developing a product solution in the “Solution Space.”

First, the Problem Space defines operational concepts based on the user’s desired mission. The operational concept is studied from the stakeholder’s view and describes how these stakeholders expect the system to function. This operational concept eventually forms the basis for the requirement and functional architectures which are part

of the Solution Space. Once the operational architecture is developed and analyzed the requirements; operational, functional, and non-functional, must be defined and examined to ensure that the requirements are feasible.

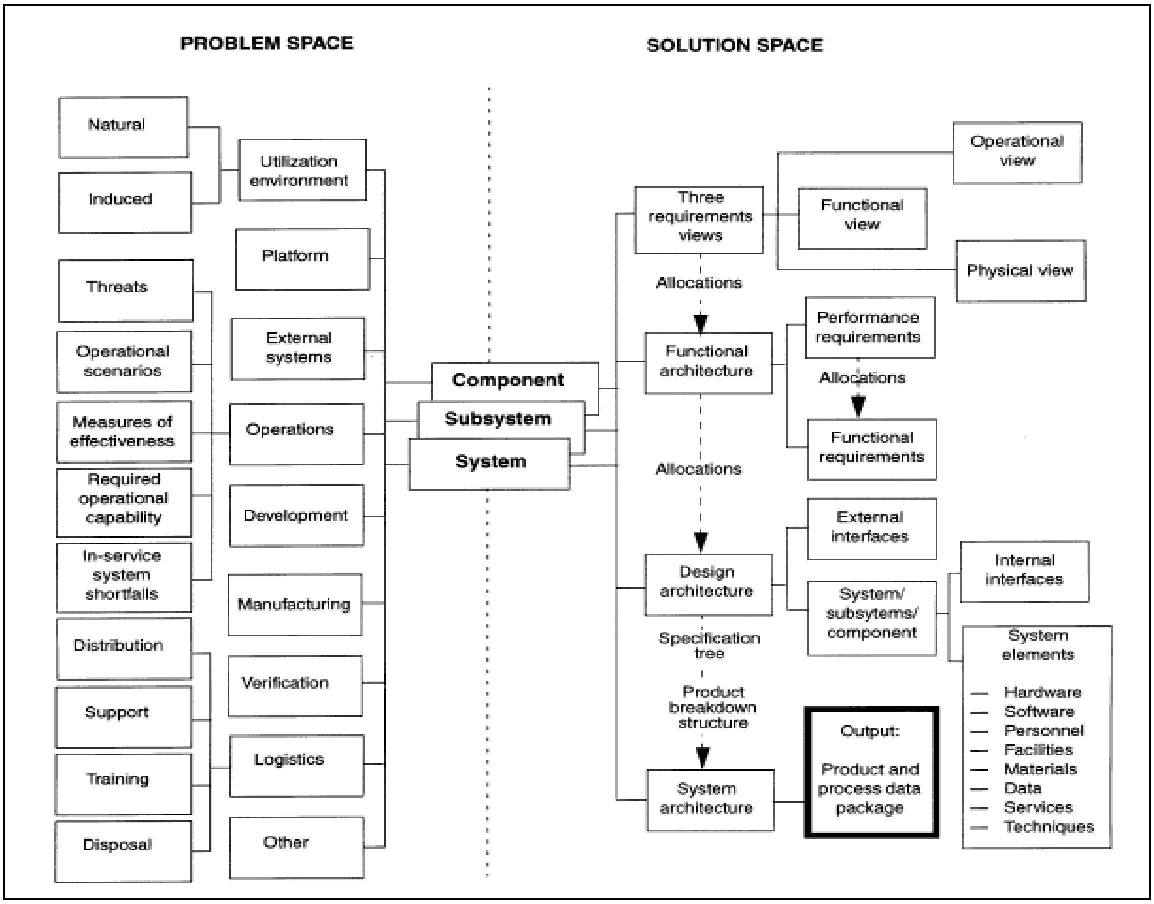

Figure 1. Problem and solution space for SE (From IEEE Std 1220–1998)

Next, the functional architecture should be developed based on the mission and requirements. The functional architecture defines “What the systems must do.” The functional architecture can be viewed as a hierarchical model of the functions performed by the system, eventually allocated to the system's components. Finally, the physical architecture is created based on the allocation from the functional architecture.

The physical architecture defines “How the system will do” the functions in terms of physical resources. The physical architecture provides all resources for every function identified in the functional architecture. It is a hierarchical description of the resources which comprise the system. This hierarchy begins with the system and system’s top level

components and eventually ends at the configuration items (CIs). The U.S. Navy uses a work breakdown structure (WBS) to categorize the physical architecture of the combatant ship system.

B. TRENDS OF NAVAL SHIP CONCEPT DESIGN PROCESS IN TERMS OF SYSTEMS ENGINEERING

1. NATO Specialist Team

A NATO specialist team was established to set up a system engineering framework to evaluate the cost effectiveness of new technology from a total ship system perspective (Brouwer, 2008). The NATO Maritime Capability Group dealt with ship design and maritime mobility (NATO AC141 / MCG/6) and has consisted of experts from NATO members and Partnership for Peace (PfP) countries. Their framework is based on system engineering processes and activities relevant to a concept exploration phase in ship design. The specialist team determined that the interaction between operational analysis and ship design models is not well established. Therefore they developed a framework in order to gain insight into the key parameters driving total ship cost effectiveness in its operational environment. This NATO specialist team described following five systems engineering processes and activities in their concept exploration phase:

- Stakeholder requirement definition

  Establish the overall mission, define operating areas and environments and identify opposing forces and threats

- Requirement analysis

  Define roles of allied forces and systems, naval system operational requirements, measure of effectiveness (MOE), tasks, develop high-level conceptual architectures of possible solutions, execute engagement modeling, decompose to lower level functions and their measures of performance

- Synthesis Architectural design

  Develop alternative ship/fleet concept design

- Verification

  Determine actual measures of performance (MOPs) for alternative designs, estimate acquisition and life cycle cost

- Validation

  Model alternative designs in systems and scenarios, aggregate MOEs to MOE for total system on mission level, assess cost effectiveness for determining superior design

Figure 2 briefly shows these processes. The framework closes the loop from the definition of the overall operational objectives, through engagement modeling, synthesis and design evaluation, back to the validation of these operational requirements. The most important issue in this design process framework is the interaction between operations research and ship performance assessment models, which is essential in identifying the real key parameters. By identifying the key performance parameters, the initial framework for cost effectiveness evaluation has been set up. It provides decision support information for technology development prioritization. The NATO Specialist team is testing the framework for a relatively simple scenario first, in order to get a feel about its applicability and the practical problems.

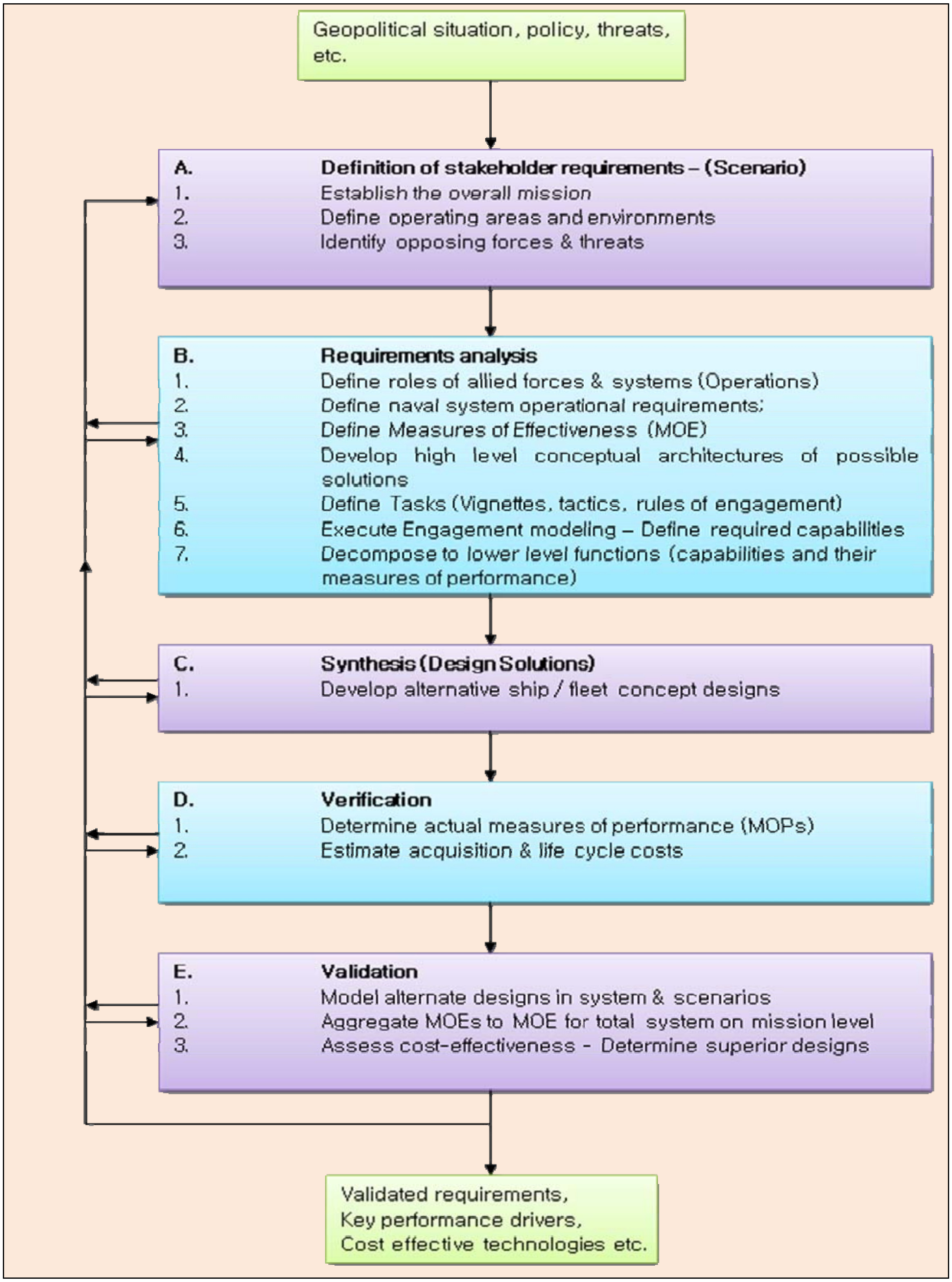

Figure 2. SE process of NATO Specialist team (From Brouwer, 2008)

2. NPS TSSE Example

The Naval Postgraduate School (NPS) Total Ship Systems Engineering (TSSE) program team has implemented an integrated design project using a total ship systems approach reflecting current naval and systems engineering trends integrated into the final design. The TSSE Team's design process represents a current systems-engineering approach applied to naval combatant ship concept design.

The 2009 TSSE project is to design an electric surface combatant ship with a Massachusetts Institute of Technology (MIT) project team. The NPS TSSE team is following the systems-engineering applied design process as shown in Figure 3.

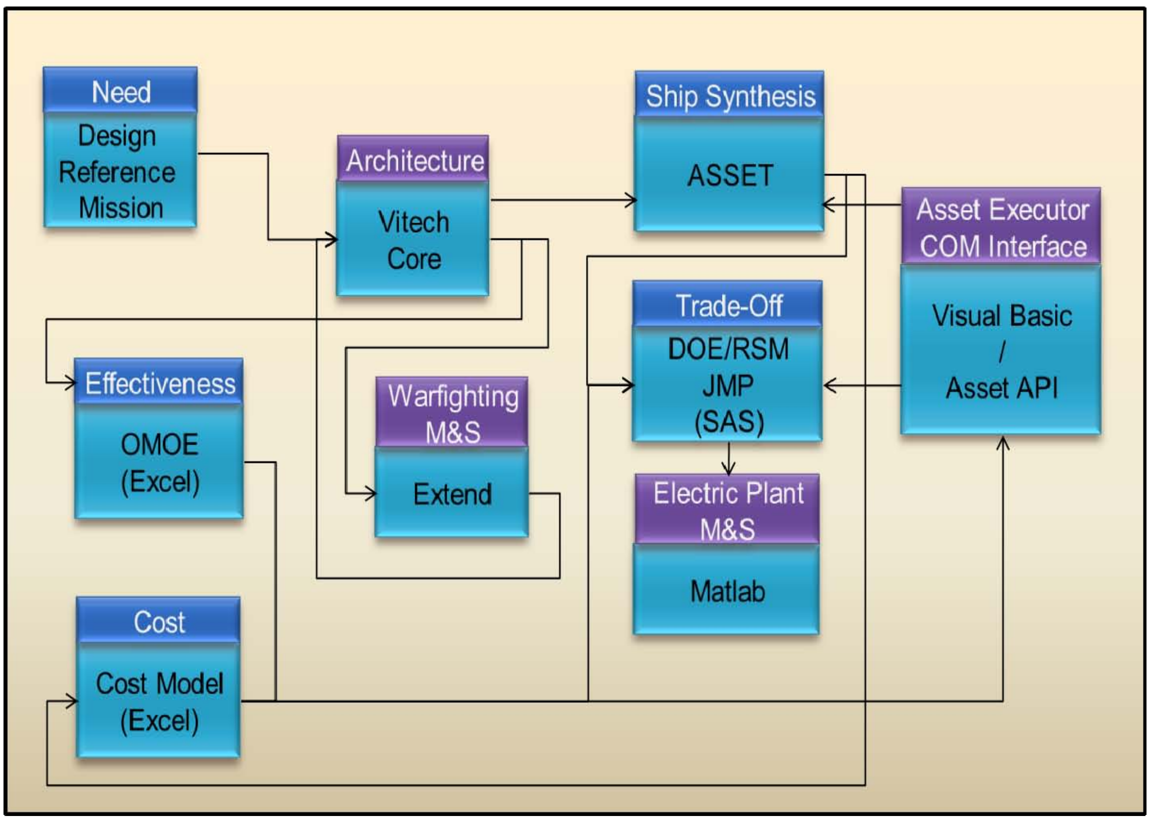

Figure 3. NPS TSSE team SE applied design process

First, the TSSE team develops a design reference mission (DRM) (Skolnick and Wilkins, 2000). As part of this development, a stakeholder's survey is conducted to gather stakeholder preferences. All data identified in the DRM goes into a SE architecture development tool, Vitech CORE. The Vitech CORE tool enables the system architect to

create functional, physical, and operational views and provides the systems information to warfighting Modeling and Simulation (M&S) models, a ship synthesis model, a cost model, and an Overall Measures of Effectiveness (OMOE) model. Effectiveness and cost are estimated to trade off the ship design alternatives. The Cost/OMOE and ship synthesis models are performed iteratively. During this optimization process, cost is minimized, and effectiveness is maximized. The final design is chosen from a cost-effective trade-off study, identifying the set of non-dominated alternatives for the stakeholders to use in a total ship system trade off.

C. CHAPTER SUMMARY

Systems engineering is an interdisciplinary engineering management process that enables the realization of successful systems that meet the user's need for the purpose of applying a systems engineering approach to complex system projects in order to design, build, and operate the system in the most cost-effective way. Numerous organizations are currently trying to apply systems engineering processes to their design projects, but they use their own processes and tools. Therefore, the R.O.K. Navy needs to develop and refine its own systems engineering process which reflects the R.O.K. Navy's needs as well as a basic SE concept.

III. NAVAL SHIP CONCEPT DESIGN PROCESS

A. INTRODUCTION

The purpose of conceptual design is to identify the feasible design possibilities in order to find the most effective ship through synthesizing and analyzing possible options. The concept design stage is an essential stage despite the limited number of engineers involved and the ambiguity of the initial information. This chapter shows the current concept design process of the R.O.K. Navy and U.S. Navy's TSSE program and compares those two concept design processes. Finally, this chapter presents an appropriate concept design process for the R.O.K. Navy.

B. CONCEPT DESIGN PROCESS OF R.O.K AND U.S NAVY

1. R.O.K Navy's Concept Design Process

The R.O.K. naval ship design approach has experienced fundamental changes over the past 40 years due to the challenges posed by new missions, new technologies, new threats, and especially new policies toward North Korea.

In today's defense environment, and with current technologies, the R.O.K, Navy has attempted to apply the SE concept to ship design. It is trying to evaluate the costs and benefits of different strategies, and also trying to ensure that ships are designed safely and effectively to meet the Navy's needs. One aspect of these changes is that the R.O.K. Navy built the Technical Information System for Naval Engineering (TISNE) in 2008. The TISNE is a SE tool for systems architecture and ship synthesis.

The basic concept of TISNE is Continuous Acquisition and Life-cycle Support (CALS) and Knowledge Management System (KMS). As shown in Figure 4, the TISNE consists of four layers: User Interface Layer, Application Layer, Integration Layer, and Database Layer. The User Interface Layer provides Integrated Graphical User Interface that forms a web based TISNE Portal. The Application Layer consists of three systems: Design and Engineering System (DES), Project Management System (PMS), and Knowledge Management System (KMS).

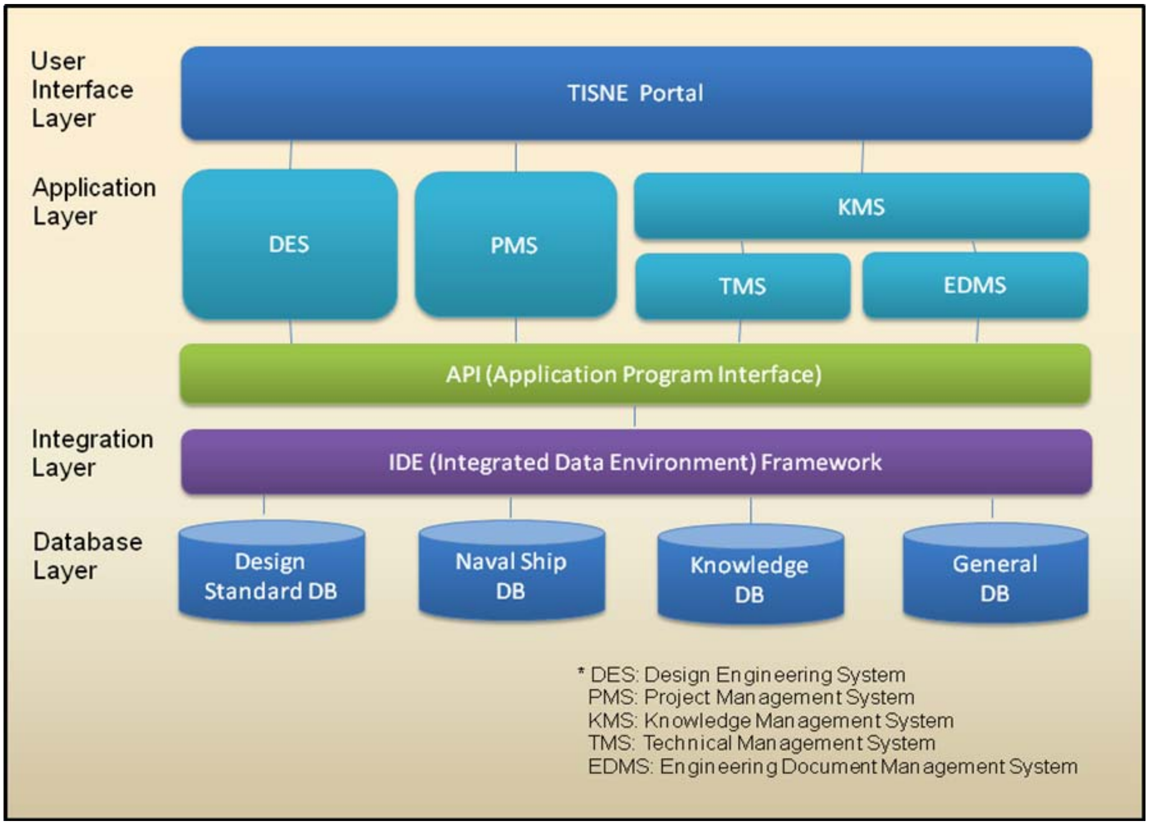

Figure 4. System architecture of TISNE (From Sim, 2004)

The Integrated Data Environment (IDE) Framework is an integrated management system for databases which provides an environment for engineering data storage, management, and usages. The Database Layer is an aggregate of ship design and engineering technical information and data. It includes data bases of design standards, naval ships, and general knowledge.

The Application Layer is the main core of the whole system. The R.O.K. ship design officers carry out naval ship designs using the Application Layer: PMS, KMS, and DES. First, engineers can manage the design project effectively in all life cycles including Research and Development (R&D), Acquisition, Operation, and Disposal using the PMS. Based on the PMS, naval ship concept design can be conducted using DES and KMS. All data, including military standards, design reports, hull form, drawings, and general technologies are stored in KMS. Finally, new naval ship design can be performed in the DES. The three systems (PMS, KMS, and DES) are operated complementarily.

Design output derived from the DES should go to the PMS and KMS. The new design data becomes a form of a KMS database. Figure 5 represent this complementary relationship between the three systems in the Application Layer.

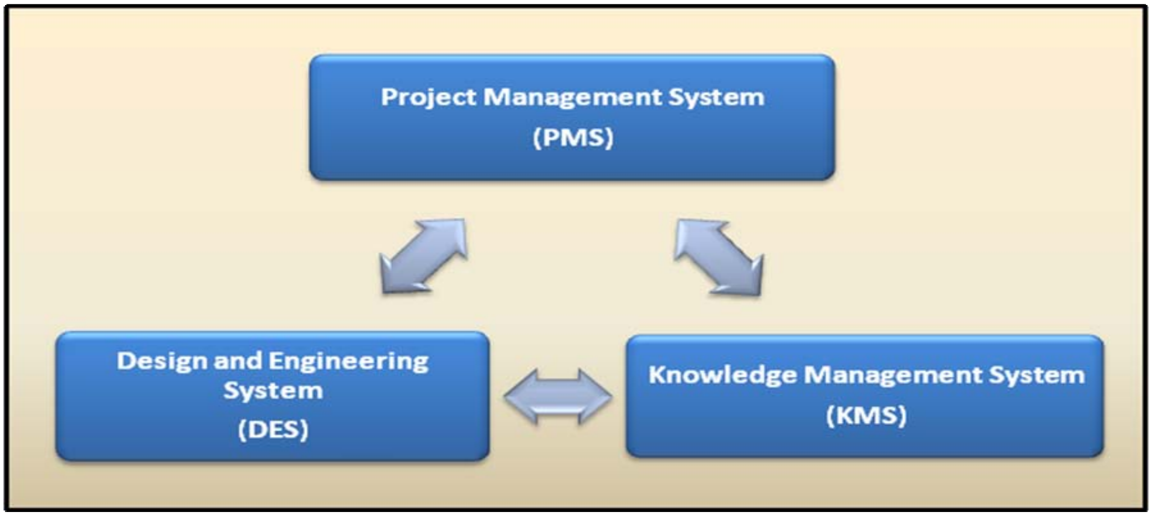

Figure 5. The relationship between PMS, KMS, and DES

As stated above, through TISNE, almost all concept design processes can be performed. Figure 6 shows the current R.O.K. Navy concept design process using TISNE.

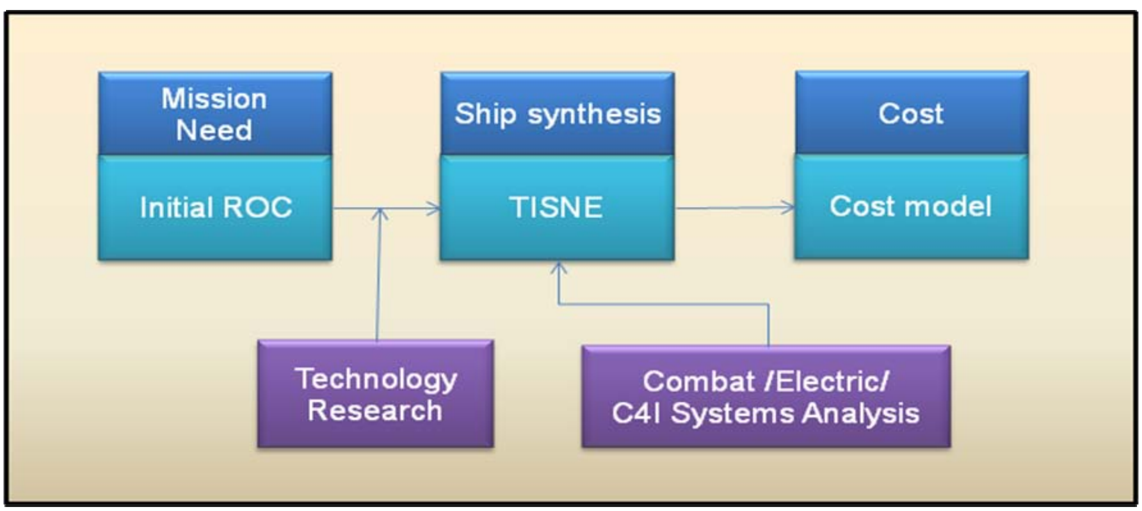

Figure 6. The R.O.K. Navy concept design process using TISNE

- Based on the initial ROC (Requirements of Operational Capability) and given mission, the designer studies operational concepts and performs technology research.

- From TISNE (especially DES), the designer performs ship synthesis as shown in Figure 7.

- Combat, electric and C4I systems are selected through trade-off studies of alternatives.

- Based on an achieved final design, the lead ship acquisition cost is estimated.

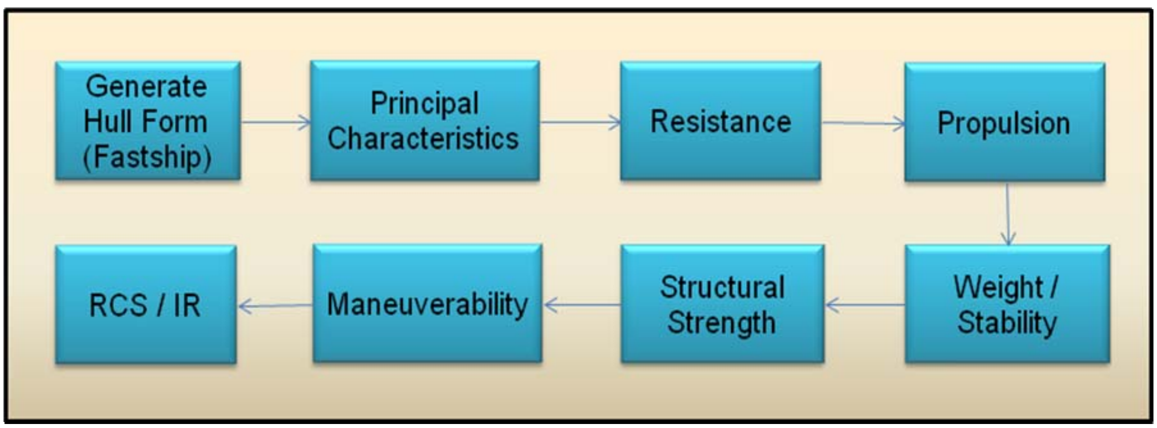

Figure 7. Ship synthesis process of DES

Ship synthesis is performed through DES as shown above. DES includes Fastship, which can help to generate the hull form. A new hull form can be created or revised from the stored one in KMS. If the hull form is determined in Fastship, it goes into the ship synthesis program. The principle of DES in ship synthesis is an iterative design spiral. The designers dictate the parameters to the system and modify the parameter that conflicts with one or more other parameters until satisfying all aspects. Therefore, the final design is a variation of the designer’s vision. This can be referred as a trial-and-error method.

2. U.S. Navy's Concept Design Process

The concept studies, which are the first step of the ship design process, occur before Milestone A. As shown in Figure 8, Defense Acquisition integrates with Joint Capabilities Integration and Development System (JCIDS) which plays an important role in identifying the operational capabilities required by the warfighters. JCIDS is based on a series of top-down analyses derived from formal strategic level guidance such as the National Security Strategy, National Defense Strategy, and the Joint Vision 2020, and the Report of the Quadrennial Defense Review (Defense Acquisition Guidebook, 2008).

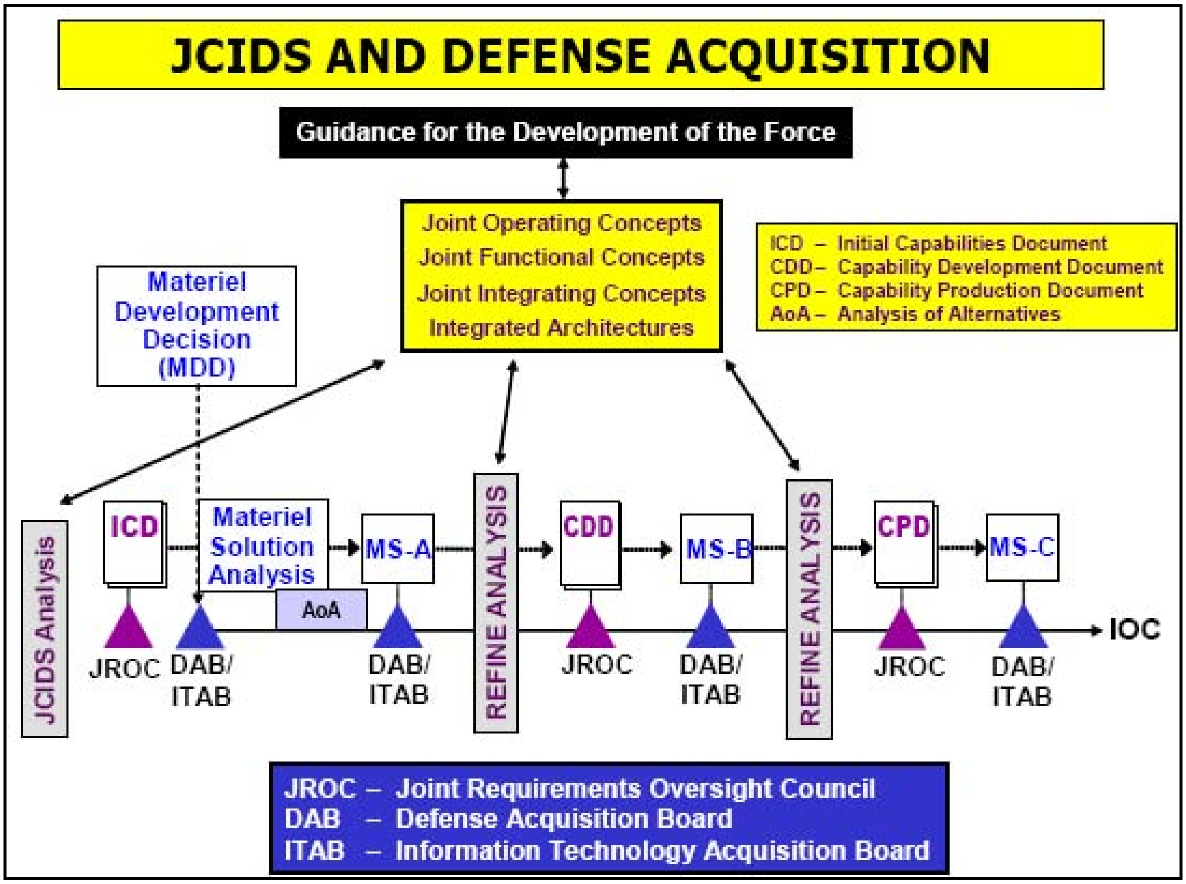

Figure 8. JCIDS and Defense Acquisition (From Defense Acquisition Guidebook, 2008)

These top-down analyses focus on the capabilities in the context of integrated architectures of multiple interoperable concepts rather than the capabilities of an individual concept. From these concepts, the JCIDS analysis process defines operational capability gaps. These gaps are defined by a combination of materiel solutions such as a

technical combatant ship design. These combinations of materiel solutions lead to Initial Capabilities Document (ICD—formerly called a Mission Need Statement [MNS]). Milestone A occurs after DoD approval of the ICD. Feasibility studies are the second step of the concept design. Their primary objective is to support the Analysis of Alternatives (AoA), which describes different solutions to satisfy the ICD. A materiel solution ranges from modifying existing ships to developing a new concept. The number of feasibility designs can range from a handful to hundreds, depending on the number of studies requested by the CNO's staff. The availability of computer synthesis models has broadened the scope AoA (Hootman & Tibbitts, 1992).

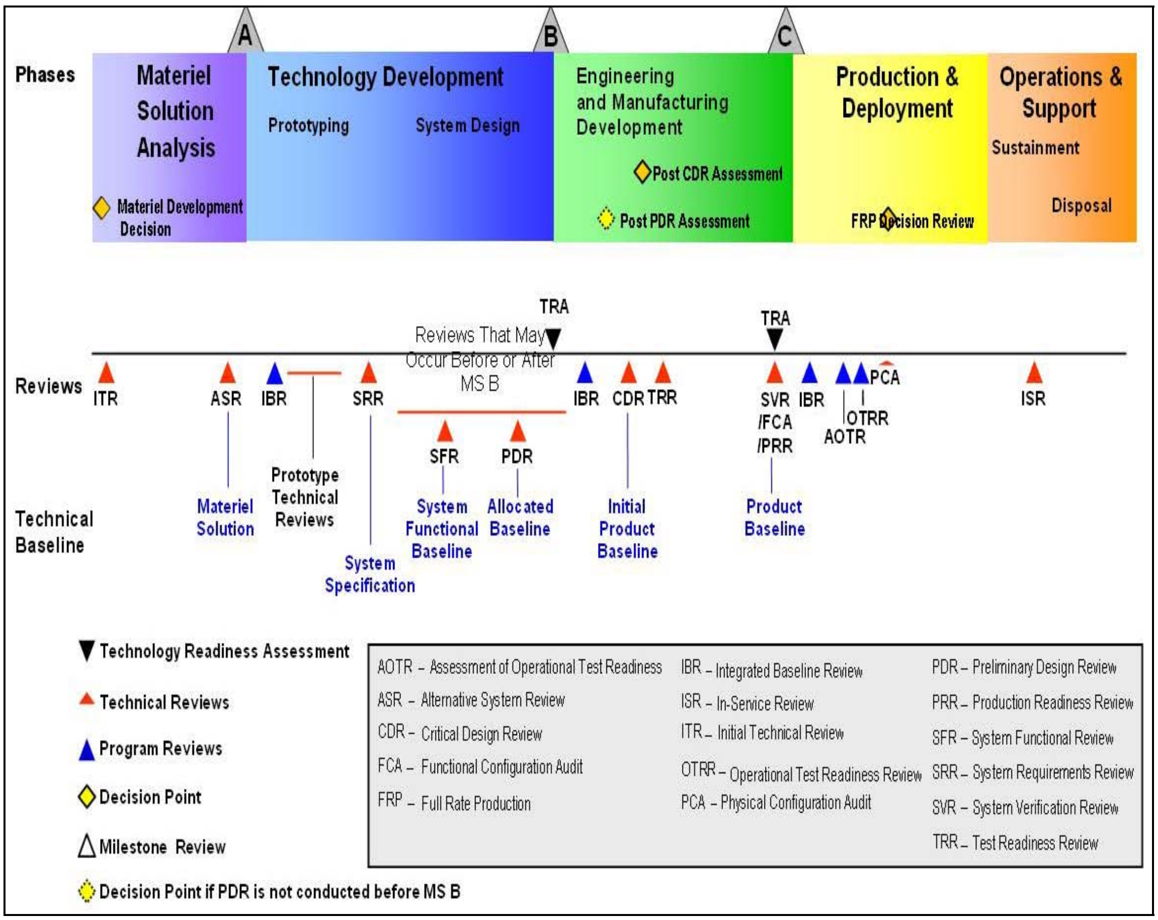

Figure 9. Systems engineering technical review timing (From Defense Acquisition Guidebook, 2008)

The AoA phase concentrates on defining basic ship functions such as speed, endurance, payload, displacement and design margin, placing the emphasis on developing alternatives that are consistent and relatively appropriate in relation to each other.

Meanwhile, the U.S. Navy is applying a SE process to defense acquisition as shown in Figure 9. However, there are many SE processes and tools for a SE process and each organization follows their own design processes and tools. Despite these varieties, the general SE applied concept design process is as shown in Figure 10. This basic process is very similar to the NPS TSSE team's process, which is explained in Chapter II. A detailed description of each step is as follows.

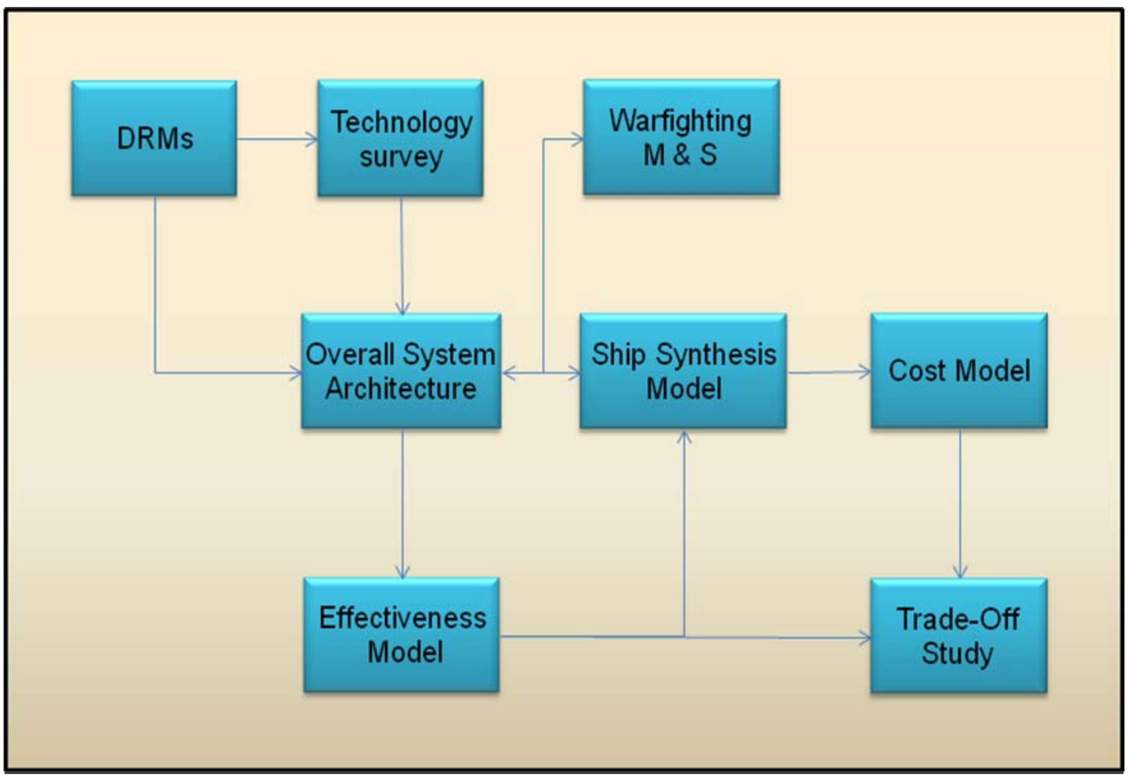

Figure 10. SE applied U.S. Navy concept design process

a. Design Reference Mission

The requirements are developed based on Design Reference Mission (DRMs), which is in the "Problem Space." The DRMs are comprised of operational and tactical situations. The DRMs progress via the following steps is shown in Figure 11.

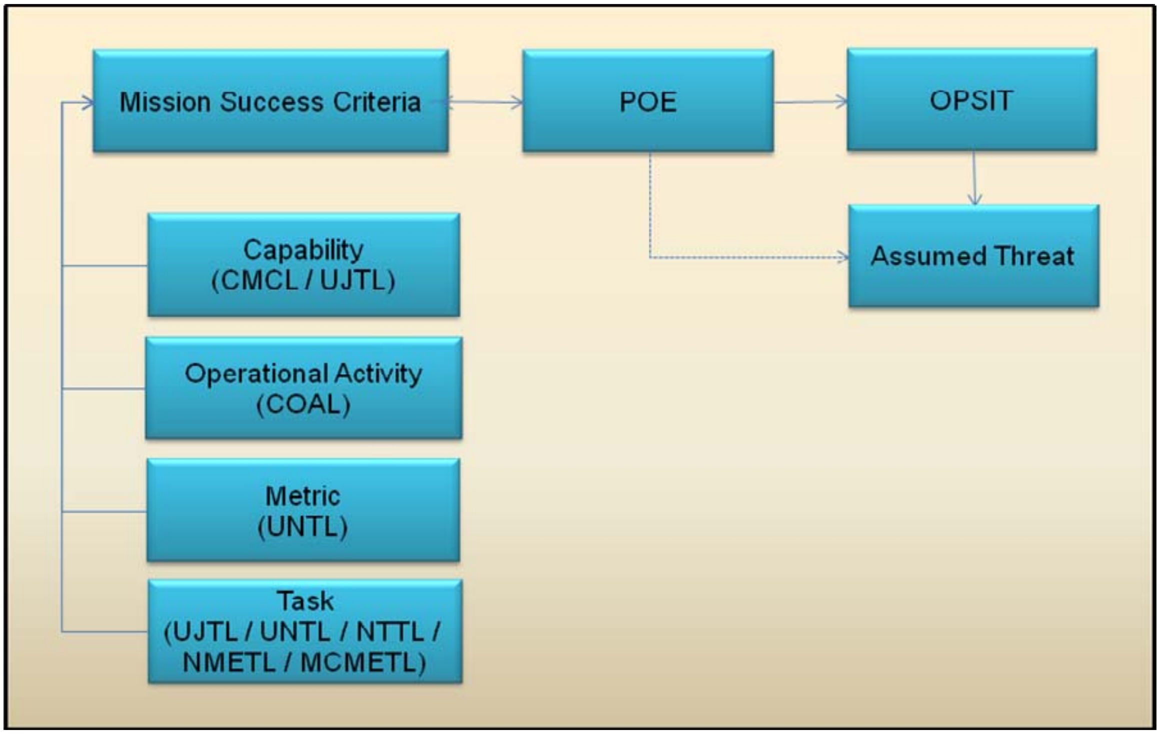

Figure 11. DRMs development step

The first step is to develop the mission success criteria. In order to determine what capabilities will be necessary for the system, the designers should use a standard list of Joint and Naval Capability Terminology List (CMCL), and the Universal Joint Task List (UJTL). The UJTL (CJCSM 3500.04) is a comprehensive hierarchical listing of the tasks that can be performed by a joint military force. It serves as a common language and reference system for joint force commanders, combat developers, and trainers and provides a basis for describing joint requirements, capabilities, and combat activities. Then, map those capabilities to Operational Activities found in the COAL. From those, the designers get the tasks from the Naval Tactical Task List (NTTL) and the Mission Essential Task List (METL). The metrics for each of those tasks can be found in the Universal Naval Task List (UNTL). The UNTL is a combination of the NTTL, and the Marine Corps Task List (MCTL). It contains a comprehensive hierarchical listing of the tasks that can be performed by a naval force, describes the variables in the environment that can affect the performance of a given task, and provides measures of performance that can be applied by a commander to set a standard of expected

performance. The UNTL identifies “what” is to be performed in terms common to all Services, but does not address “how” a task is to be performed, or “who” is to perform the task (UNTL 3.0, 2007).

Picking a scenario is the next step of the DRM. The Projected Operational Environment (POE) is the environment basis for the DRM. The POE is the environment in which the ship is expected to operate, including factors such as the climate.

Picking the operational situations (OPSIT) is the third step. The location of the execution of the mission can be specific or fictional, but must be realistic. It is helpful and suggested that a geographic description be included when describing location. Even if using a fictional location, finding a nondescript piece of land/water that will work is suggested. Finally, the designer should develop an assumed threat situation, taken from POEs. This is where characteristics of the threat will be discussed along with specific types of weapons, vehicles, and tactics. Also, the state of surroundings and weather that will play a role in the threat must be described.

b. Overall System Architecture

Advanced systems engineering approaches have been developed to create well-defined systems architectures. The Vitech CORE tool is used at the NPS for system architecture development. The CORE tool implements a Model Based Systems Engineering (MBSE) approach to developing an architecture model and any related DoDAF views (Estefan, 2008; Vitech CORE, 2007). System architecture is defined as an arrangement of elements and interconnections, and any policy that guides the development and/or operation, which is consistent with the U.S. Navy. The interrelationships among architecture elements are depicted in Figure 12.

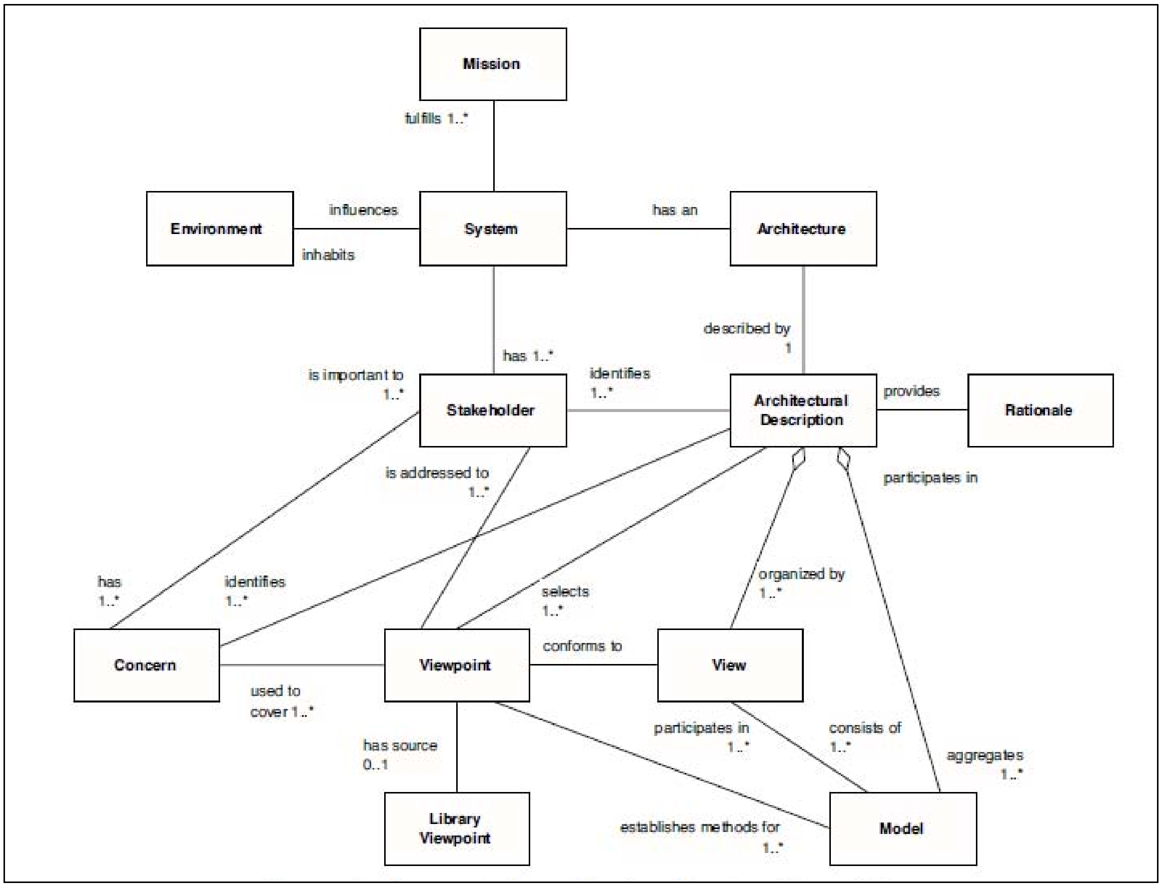

Figure 12. Conceptual model of architectural description (From IEEE Std 1471-2000)

Multiple architectural 'views' are needed to allow stakeholders to communicate with the architects and other stakeholders in their own language to ensure their concerns are addressed. All views are derived from a single system structure, the architecture, with each view acting as a lens projecting an image in the stakeholder's own native language. Architecture, then, exists for the purpose of achieving a well-defined system in all domains, such that the eventual system developed will meet operator's desired effectiveness (Whitcomb, 2009).

c. Ship Synthesis Model

The purpose of the ship synthesis model is to balance the design in an engineering perspective, and calculate objective attributes for a given set of design

variable values. It performs computation for the various naval architectural domains, such as hull form, subdivision, structure, resistance, propulsion, machinery, space and hydrostatics.

A variety of methods are used to predict the characteristics and performance of the total ship, including direct calculation, analysis of historical data, simplified direct calculations calibrated to known data, and direct input from external calculations. Specialized techniques must be used to allow the development of an accurate ship definition with the limited data that is available at the early stage of design.

The U.S. Navy uses its own tool, ASSET (Advanced Surface Ship Evaluation Tool), for ship synthesis as shown in Figure 13. The ASSET tool is a ship design synthesis computer program with a common windows-based executive for early-stage ship design.

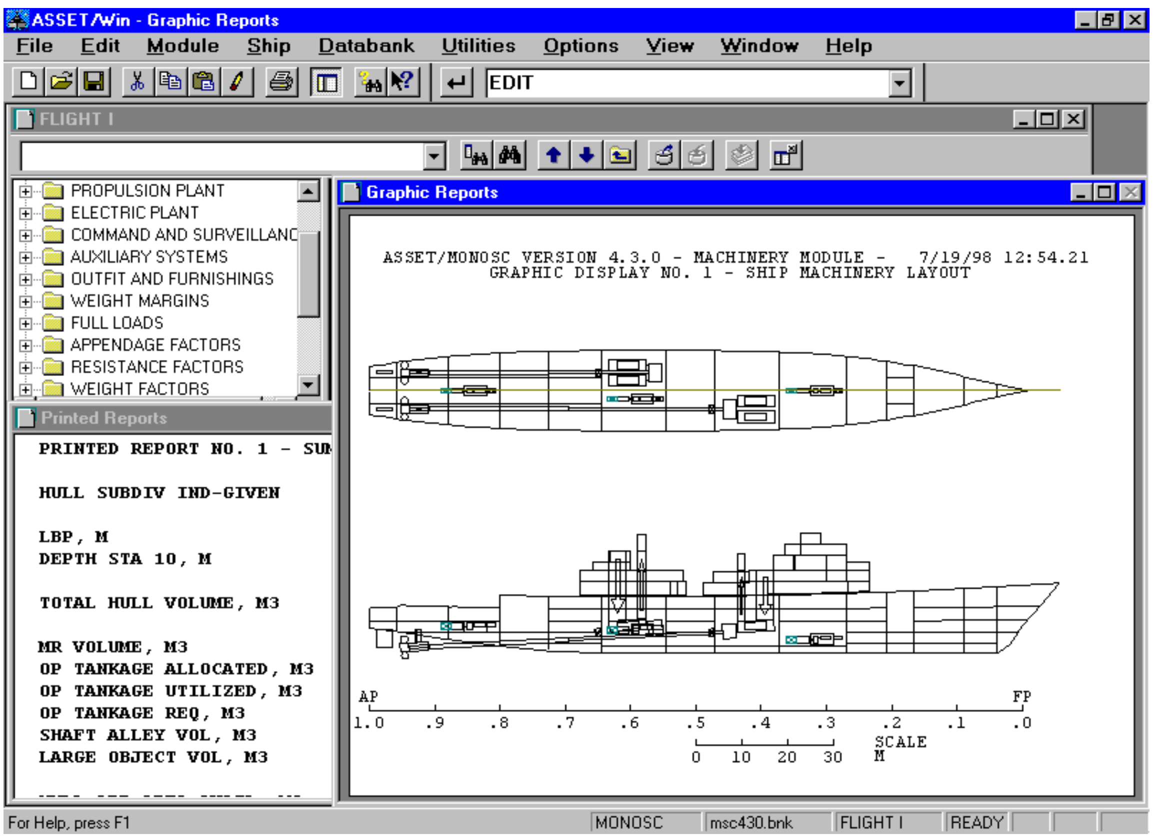

Figure 13. ASSET overview (From Koleser, 2005)

The primary purpose of ASSET is performing the initial prediction of ship physical and performance characteristics based on mission requirements. ASSET is currently being used in the design of several future U.S. Navy ships such as DDX, CVNX, T-ADCX.

Figure 14 describes the ASSET module structure of version 4. ASSET has computational and Input / Output support module. The computational module includes synthesis modules such as hull geometry, hull subdivision, aviation support, deckhouse, hull structure, appendages, resistance, propeller, machinery, auxiliary system, weight, space, and design summary. Analysis modules calculate the performance characteristics of a feasible design.

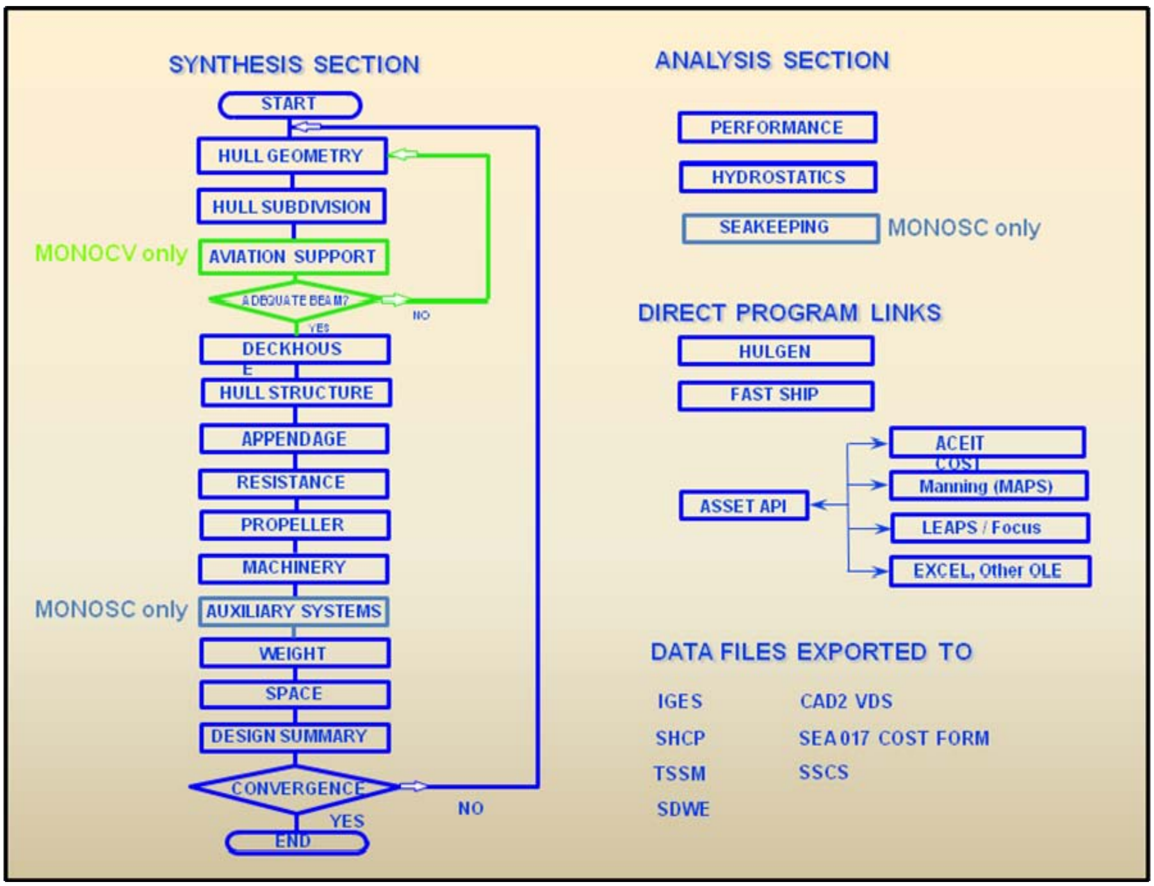

Figure 14. ASSET module structure of version 4 (From Koleser, 2005)

After the designer inputs the requirements and the initial configuration, the synthesis process is run. During the synthesis, the hull and deckhouse geometry may be

changed to meet stability requirements and subdivision, structure, and appendages are recalculated. Resistance and propeller determine powering requirements for the new geometry and the current weight/displacement and speed. The propulsion and electric plant may be resized to meet the powering requirements. Weight/Displacement and internal space requirements are updated. It continues to the modules in sequence until all parameters have converged and all calculations are for a consistent set of conditions. However, ASSET does not provide arrangement of the ship. Flight deck and other topside arrangements must be done outside of ASSET. Other programs such as Excel spreadsheets, Simplified Ship Synthesis Model (SSSM), AVEVA Marine can also provide a ship design model, but ASSET is one of the only tools that can be synthesize a naval combatant from a small number of naval architectural variables.

d. Overall Measures of Effectiveness Model

MOE metrics are stated from the acquirer viewpoint, focusing on the system's capability to achieve mission success within the total operational environment. The MOEs are used to compare operational alternatives, investigate performance sensitivities to changes in assumptions from the user's view, and to define operational requirement values (Roelder & Jones, 2007).

> Early in the naval ship design process, designers and engineers require a working model to quantify operators' and policy-makers' definition of mission effectiveness (MOE), and to define its functional relationship to ship and ship system measures of performance (MOPs). This quantitative assessment of effectiveness is fundamental to a structured optimization process. (Brown & Salcedo, 2003)

There are a few methods and tools for finding the OMOE value of a ship. Among those, a spreadsheet OMOE model is adapted here for deriving OMOE. The basic steps of the spreadsheet OMOE model are shown in Figure 15.

First, the designer addresses the criteria system must accomplish, based on DRMs. Specific criteria are determined from a stakeholders' criteria survey. These criteria are defined as MOEs. An appropriate set of criteria is organized using decision making tools, such as AHP (Analytical Hierarchy Process).

Those tools are good methods for generating the priorities and relative weights in order to determine which aspects of the mission capabilities are most important. Using Quality Function Deployment (QFD) is a way to translate customer needs and requirements ("whats") into engineering characteristics for a ship such as design characteristics, functions, and forms ("hows"). For combatant design, QFD is structured to determine the relationship between MOEs and MOPs and stakeholder need.

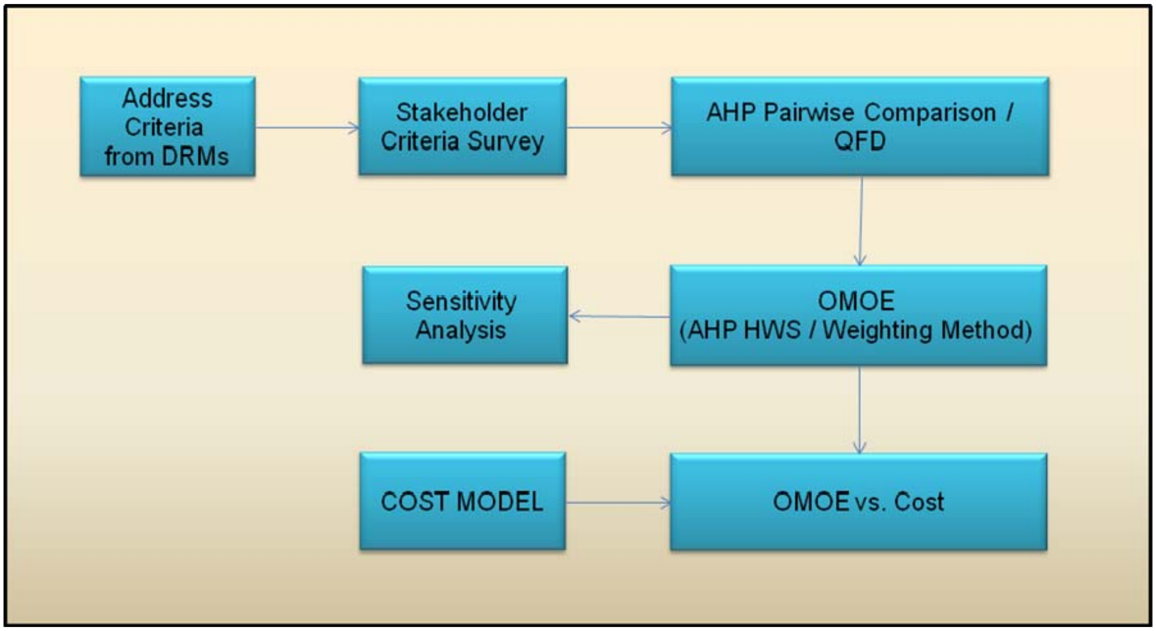

Figure 15. OMOE model process

The OMOE is the roll up of all the individual MOEs as defined in equation (1):

$$OMOE|_{SYSTEM} = f\{w_i \cdot [g_i(MoP_k)]\} \quad (1)$$

Where: w = Weighting Factors

f, g = Combinatory functions

The OMOE can be mathematically defined in several different forms, and each can be used to present decision metrics to the stakeholders. The maximum value of OMOE is 1.

The next step is to perform a sensitivity analysis for each OMOE weight. The weights computed in the AHP method are subjectively determined, so the solution sensitivity to variation in weights is important. Sensitivity analysis helps to show the robustness of the potential solutions to the variation of the weights used in the OMOE calculation. If the solution is robust to an attribute weight change, then the selection of a particular solution alternative, with respect to OMOE, will remain constant.

e. Cost Model

Cost is estimated using a spreadsheet model. The spreadsheet cost model calculates initial acquisition cost (Lead Ship Cost and Follow Ship Cost) and LCC (Life Cycle Cost) which is all of the expenses associated with a ship that occurs during its life. These include all acquisition (research and development, design, production and construction), operation and disposal costs. Comparing LCCs is a common way to evaluate different alternatives. For early stage concept studies, parametric methods are typically used, as shown in Figure 16.

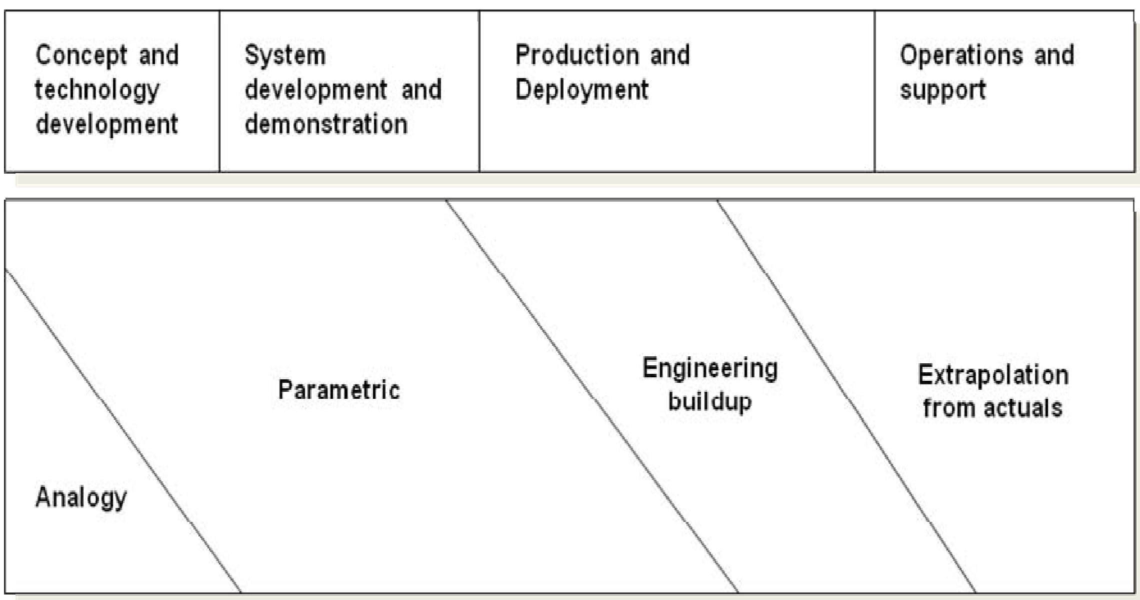

Figure 16. Cost estimation process (From Papoulias, 2009)

f. Design Optimization

The designer can combine the design variables in hundreds of ways. A process for finding the best combination among the alternatives from a set of feasible options must be implemented.

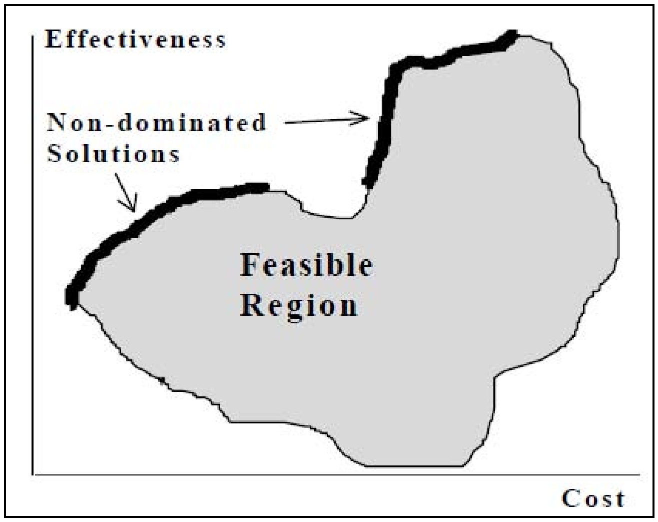

Figure 17. Two objective attributes space (From Brown &Thomas, 1998)

In naval combatant ship design, two major objectives, military effectiveness and cost, are typically considered. Figure 17 simply shows a two-objective (cost and effectiveness) concept, with the non-dominated (Pareto) frontier identified. Design selection should be done from these non-dominated solutions depending on the decision maker's preferences for cost and effectiveness.

3. Comparison of the Two Concept Design Processes

The current R.O.K. naval ship design process and the TSSE process applied to U.S. naval combatant ship design are quite different in some aspects. Table 1 shows a summary comparison result of the two naval ship concept design process, with X indicating that methods are not applied, and O indicating that methods are applied.

Table 1. Comparison of two countries' naval ship concept design process

Process	R.O.K Navy	U.S Navy TSSE
Requirements	Initial ROC	DRMs
System Architecture	X	DoDAF Vitech CORE IBM System Architect
Ship synthesis	O (TISNE)	O (ASSET/AVEVA marine/Excel/SSSM)
OMOE Model	X	O (Excel)
Cost Model	O (Excel)	O (Excel)
Multi Objective Optimization	X	O (JMP, Excel)

TISNE was developed as part of a device to utilize the SE approach in the R.O.K. Navy but it still needs improvement. Through the TISNE, ship synthesis can be achieved. However, TISNE does not provide system architecture and optimization processes using the cost and effectiveness analysis functions. Effectiveness analysis has also been disregarded in the R.O.K. process of concept design.

C. PROPOSED CONCEPT DESIGN PROCESS FOR R.O.K. NAVY

Based on the above comparison, a new concept design process for the R.O.K. Navy is proposed.

As shown in Figure 18, the biggest changes of the concept design process compared to the previous process in the R.O.K. Navy are the addition of system architecture and OMOE models.

The baseline of developing the new design process was the TISNE. As stated before, the TISNE development was completed in 2008 as part of the SE approach in the

R.O.K. Navy. This means that the R.O.K. Navy is willing to continue to use the current system and improve it if necessary. Therefore, systems architecture functions along with PMS, KMS, and DES in the Application Layer should be added to TISNE.

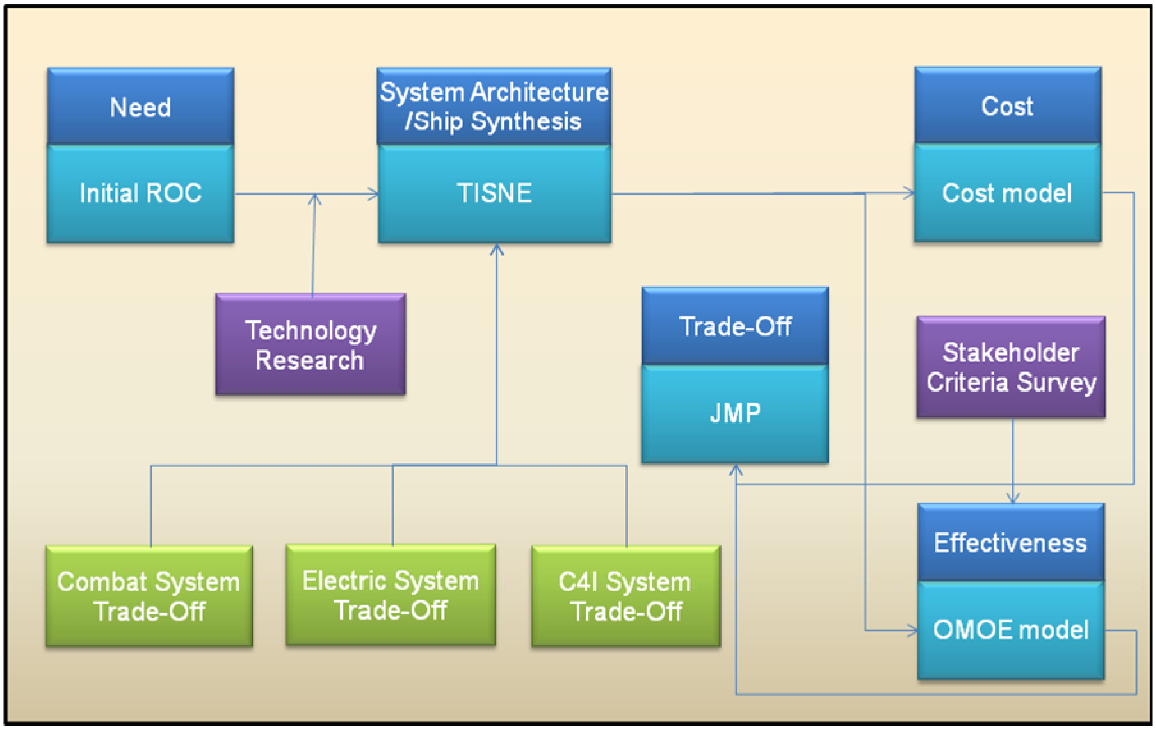

Figure 18. Newly-proposed R.O.K Navy's concept design process

The goal of this newly proposed concept design process is to optimize the cost-effectiveness of the total ship system. The OMOE model must be created with consideration of the R.O.K. Navy's perspective and its threats.

The System Architecture/Ship Synthesis block has added four SE architecture parts: operational (mission), requirements, functional architecture, and physical architecture. The following description has been developed based on the assumption that a systems architecture function is to be added to TISNE.

1. Operational Architecture

Based on given initial ROC, the designer performs an operational concept study following a DRM format and associated technology research. Mission capability should be specifically assessed. The definition of MOEs and MOPs is an essential prerequisite to

the functional and physical architecture development. A stakeholder needs and warfighting criteria survey should be provided in order to define a relationship between MOEs and MOPs.

2. Requirements

The stakeholder's need should be determined based on the mission capability desired. The stakeholder's requirement(s) such as required operational capabilities, performance constraints, goals and thresholds are derived. The stakeholder's requirement(s) can be organized using TISNE.

3. Functional Architecture

Based on the mission and the customer's requirement(s), the functional requirement(s) should be identified. Top level functional requirements might include enclose and protect, provide mobility, provide electric power, support, and warfighting. The functional requirement(s) also can be organized using TISNE.

4. Physical Architecture

The ship synthesis defines the physical architecture. The ship is balanced using the TISNE ship synthesis model, and OMOE and cost are calculated from each physical architecture alternative. Ship balance requires that physical and functional constraints are satisfied. It must have appropriate engineering feasibility assessed including stability, mobility, weight, volume, electric power, etc. Finally, by trade-off studies, alternatives are optimized in a cost effective manner, and the best selected from among non-dominated solution with stakeholder interaction.

D. CHAPTER SUMMARY

The current concept design processes of the two countries are similar in ship synthesis, but are quiet different in terms of systems architecture and cost/OMOE models. Through the two countries' concept design comparison, the newly-developed R.O.K Navy concept design process was proposed. The main changes are overall system architecture concept and cost/OMOE models. These added processes can provide cost-effective design output through a well defined and organized design SE architecture concept. A case study of the newly proposed concept design process is presented in the Chapter IV.

IV. FFX CASE STUDY

A. INTRODUCTION

This chapter presents a case study for the Future Frigate Experimental (FFX, Ulsan-I class), which is currently being constructed in the Korean Naval shipyard. This case study optimizes the ship concepts in terms of LCA (Lead Ship Acquisition Cost) and operational effectiveness. The models used in the case study are discussed and presented.

B. FFX CASE STUDY USING A NEWLY-PROPOSED CONCEPT DESIGN PROCESS

1. What is an FFX?

Figure 19. FFX graphic model

The FFX is a planned class to replace the Ulsan class and other smaller frigates. Hyundai Heavy Industries have been in charge of the detail design of the FFX. The R.O.K. Navy wants to launch 24 FFX vessels by 2020 and replace the Ulsan, Pohang, and Donghae classes as part of their efforts to bolster its coastal defense operations.

The FFX was designed for anti-ship, anti-submarine and anti-aircraft warfare, and its advanced design concept affords wide options for weapons combinations and convenient maintenance.

The main design concepts of the FFX are as follows:

- Warfighting-performance-centered design
- Designed for coastal defense operations
- Design considered maintenance and availability
- Design met requirements and military standards
- Design optimized naval architecture and combat systems

2. Mission Need

The original mission analysis and requirements were largely classified, but some data can be estimated. The FFX class will be deployed mainly near the inter-Korean maritime border and Northern Limit Line (NLL), which has served as the maritime border between the two Koreas.

The FFX will have the ability to strike and defend against threats from the air, surface and submarines. Also, it will have the ability of tactical employment in contingency and wartime operations. The missions for FFX include:

Primary Mission

- Coastal Patrol: The main force for coastal defense.

Secondary Mission

- Protect sea lane of communication (SLOC): SLOC including commercial shipping and military transport against the North Korean forces.
- Surface Combatant Force: Defense against threat with DDH, PCC and PKM at Wartime.
- Limited support non combatant or NCO operations in peacetime.

Based on those missions, following minimum requirements can be specified.

Table 2. FFX initial ROCs

Characteristic	Value
Sustained Speed	More than 30 knots
Range	More than 4,000 nm
Duration	More than 45 days
Personnel	170
Propulsion	CODOG (2 GE LM2500 gas turbine; 2 MTU 16V diesels; 2 shafts; cp props)
Combat Systems	- AAW Missiles: SAAM - ASuW Missiles: KSSM - ASW Missiles: Torpedo, TACM - Gun: 76mm or 127mm Main Gun - Self defense: CIWS - Others: Combat data system; Weapon control system; Air search and Fire control Radars; Sonars
Helo	1 or 2 LYNXES

3. Ship Synthesis

Ship synthesis is accomplished as guided by the Design of Experiments (DOE) process in order to create a Response Surface Model (RSM). Table 3 lists the alternative designs to be created, through A1 to A15 based on a central composite design. For each alternative, the factor values (Range, Payload, Margin) were input into the ship synthesis model, ASSET. The High, Medium, and Low values for the factors are defined in Table 4.

Table 3. FFX alternatives design synthesis list

Alternatives	Factors (X)		
	Range (X_1)	**Payload (X_2)**	**Margin (X_3)**
A1	M	M	H
A2	M	H	M
A3	M	M	M
A4	L	M	M
A5	M	M	L
A6	L	H	H
A7	H	L	L
A8	M	L	M
A9	H	M	M
A10	H	L	H
A11	H	H	L
A12	L	H	L
A13	L	L	L
A14	L	L	H
A15	H	H	H

Table 4. FFX DOE factor definition

DOE Factor Name	Units	Low	Middle	High
Range	NM	4000	5000	6000
Payload	Ltons	226	313	383
Margin	%	0	5	10

The ship is then balanced in ASSET, checked for feasibility, and ranked based on effectiveness and cost using an Excel spreadsheet.

4. OMOE Model

The Overall Measure of Effectiveness (OMOE) function is developed for use in trade-off studies.

Figure 20 shows an operational capability for the FFX. The MOPs are listed in Table 5. These are grouped into 5 MOEs:

- Warfighting: Combat system payload (L/M/H)
- Mobility: Sustained speed, Stability, Seakeeping
- Sustainability: Range, Duration
- Susceptibility: RCS, IR, Acoustic Signature, Magnetic Signature
- Flexible Capability: Weight Margin

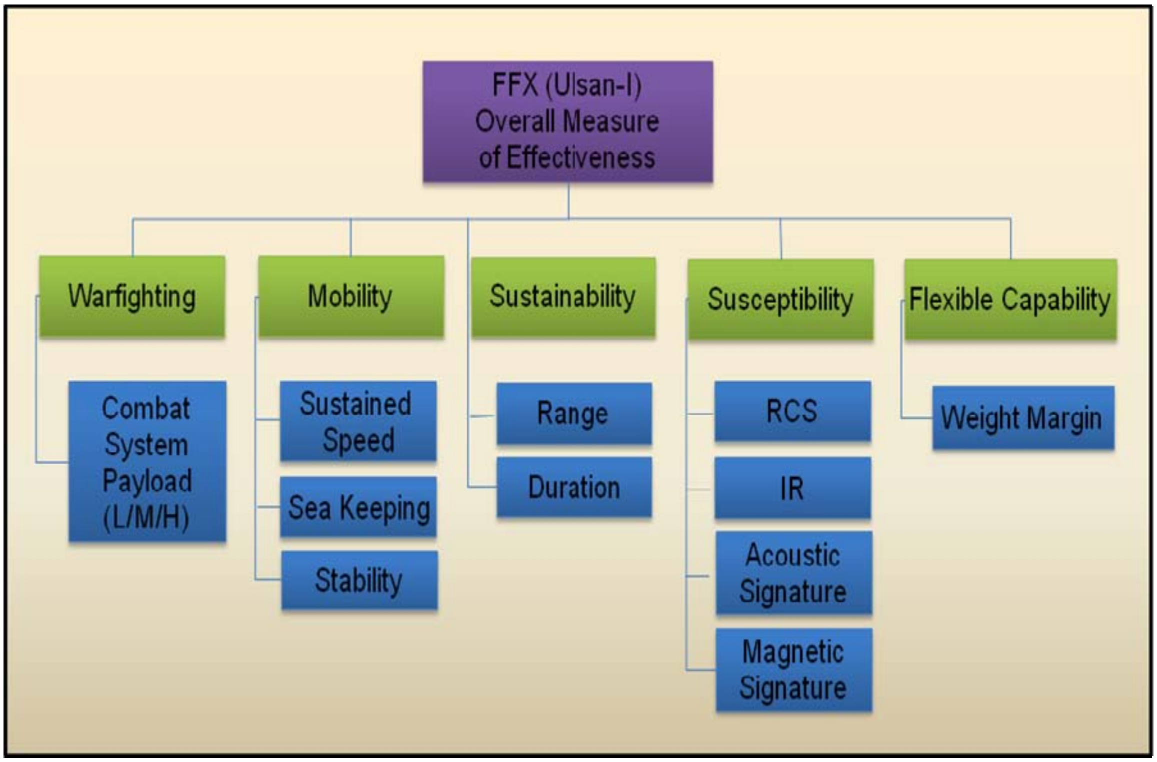

Figure 20. FFX OMOE hierarchy

Combat system payloads were scaled based on equation (2).

$$\text{Weight} = \frac{\sum\{\text{Each Level Payload (L/M/H)}\}}{\sum(\text{High Level Payload})} \tag{2}$$

The sum of the low level payload was about 226 tons, medium level payload was 313 tons, and high level payload was 383 tons each, respectively. These payloads are listed in APPENDIX A. Therefore, each level can be evaluated as an OMOE value of 0.59 for low level, 0.82 for medium level, and 1.0 for high level.

Table 5. FFX MOPs and threshold/goal

MOEs	MOPs	Threshold	Goal	Remarks
Warfighting	Combat System Payload	0	1	Level L=0.59; Level M=0.82; Level H=1.0
Mobility	Sustained Speed	30	32	Knots
	Sea Keeping	0	1	Level L=0; Level M=0.60; Level H=1.0
	Stability	0	1	
Sustainability	Range	4000	6000	NM
	Duration	45	60	Days
Susceptibility	RCS	-	-	Level L=0; Level M=0.60; Level H=1.0
	IR	-	-	
	Acoustic Signature	-	-	
	Magnetic Signature	-	-	
Flexible Capability	Weight Margin	0	10	%

Susceptibility is an important measure of performance for the FFX. But the R.O.K. Navy has not decided on the threshold and goal. They are considering a stealth design but do not have its design standards. Also, it is difficult to measure those values in the concept design stage. In this case study, therefore, the values of RCS, IR, acoustic signature, and magnetic signature were fixed at medium level.

The MOPs were weighted using a pairwise comparison as shown in Figure 21. Pairwise comparison was conducted based on the expected combat scenarios between South and North Korea.

Criteria	Criteria	1 Warfighting	2 Mobility	3 Sustainability	4 Susceptability	5 Flexible Capability	Weights
Warfighting	1	1	6	8	6	8.5	0.5080
Mobility	2	0.166667	1	7	4.5	7.5	0.2339
Sustainability	3	0.125	0.142857	1	7.5	4	0.1388
Susceptability	4	0.166667	0.222222	0.133333	1	7	0.0892
Flexible Capability	5	0.117647	0.133333	0.25	0.142857	1	0.0302
	check	0.6	0.1	0.1	0.1	0.0	1.0000

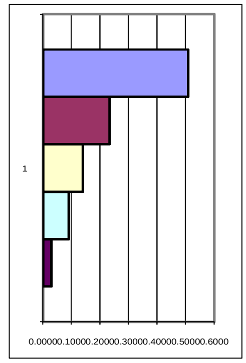

Figure 21. AHP pairwise comparison

The given weights of each attribute were based on the designer's perspective for this case. However, the stakeholders' survey is required in a real concept design. The OMOE for each alternative is defined from excel spreadsheet as shown in Figure 22.

OMOE Model

Ship name: FFX

Overall MOE_i: 0.822

MOE Weight	MOE Criteria Name		MOP Weight	MOP Attribute Name		MOP Threshold	MOP Goal	Attained
0.5080 / 0.508	Warfighting	1.00	1.000 / 6.000	Payload	1.0	0	1	1
0.2339 / 0.234	Mobility	0.69	0.600 / 3.000	Sustained Speed	0.8	30	32	31.5
			0.200 / 1.000	Seakeeping	0.6	0	1	0.60
			0.200 / 1.000	Stability	0.6	0	1	0.60
0.1388 / 0.139	Sustainability	0.50	0.500 / 0.500	Range	1.0	4000	6000	6000
			0.500 / 0.500	Duration	0.0	45	60	45.00
0.0892 / 0.089	Susceptability	0.60	0.444 / 4.000	RCS	0.6	0	1	0.60
			0.222 / 2.000	IR	0.6	0	1	0.60
			0.222 / 2.000	Acoustic Signature	0.6	0	1	0.60
			0.111 / 1.000	Magnetic Signature	0.6	0	1	0.60
0.0302 / 0.030	Flexible Capability	1.00	1.000 / 1.000	Weight Margin	1.0	0	10	10

Figure 22. FFX OMOE Model

Figure 23 shows sensitivity analysis for warfighting. The sensitivity in the warfighting weight is varied for five of the original solutions alternatives to test the OMOE sensitivity to changes in the warfighting weighting. The trend lines show the variation in those solution's OMOE with respect to a variation in warfighting weight only. Where the lines cross, the selection of a solution alternative changes, due to the changes in OMOE.

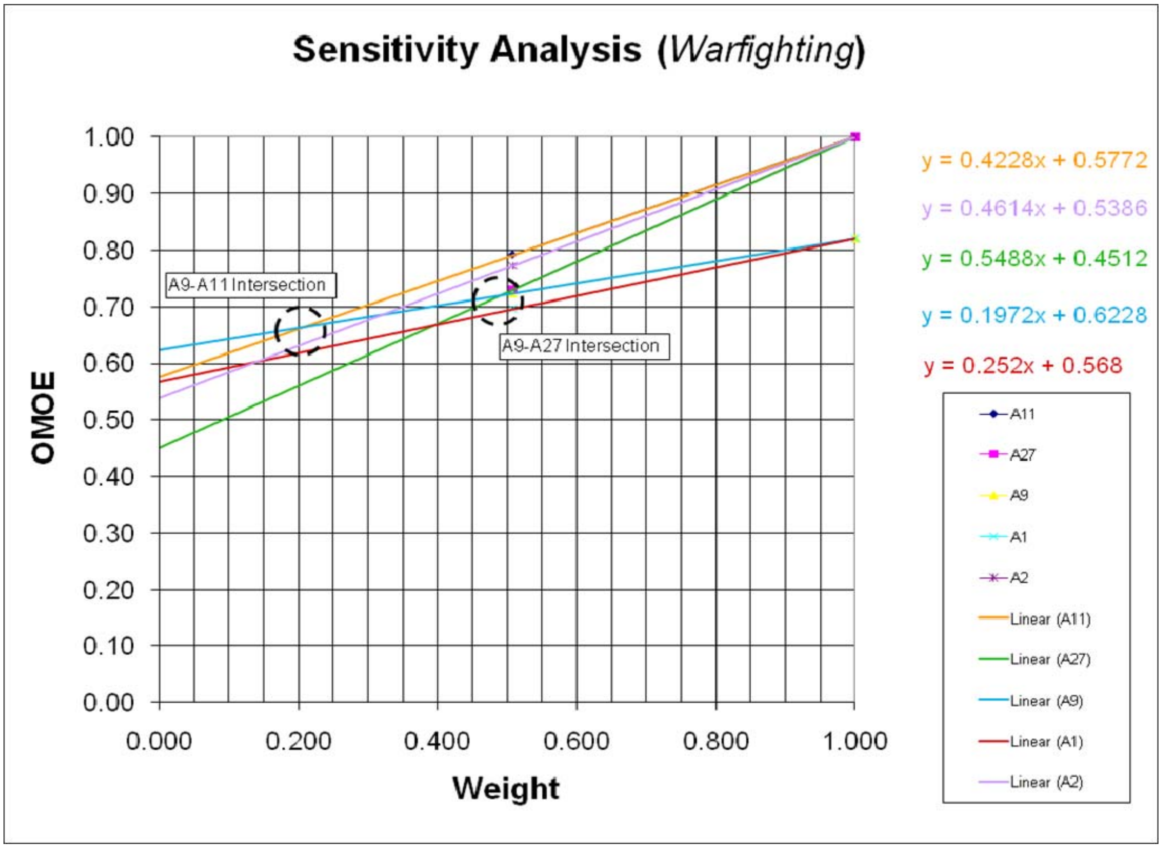

Figure 23. Sensitivity analysis for warfighting

In this case, the solutions for A9, A11, and A27 alternatives are tested. The original weight of 0.508 for warfighting is varied down to 0.20, and A11 dominates A9 over that range. Below a warfighting weight of 0.2, A9 would be selected due to the higher OMOE. The intersection of A9 and A27 is interesting, since the original weight of 0.508 has them both very close in OMOE. Any variation lower than 0.508 points to picking A9, and any variation above 0.508 indicate that A27 would be preferred. A11 dominates until warfighting weight goes below 0.2, when A9 is selected. The plot also

shows that A11 dominates in warfighting attribute over most of the high OMOE values. Sensitivity testing determines whether or not the solution that is picked has any reason to have the various subjective OMOE weights investigated, or if the solution is robust to changes in the weights.

5. Cost Model

The FFX lead-ship acquisition cost is calculated very roughly based on the R.O.K Navy's traditional cost estimation procedures, as shown in Figure 24. Almost all costs were estimated based on the displacement.

Cost Items			
Design	Labor cost	Direct	
		Indirect	
		Sum	
	General cost	Direct	Material
			Technical services
			Miniature
			Cataloging
			EVMS
			Certification
			Sum
		Indirect	
		Sum	
	Management cost		
	Profit		
	Sum		
Construction	Material cost	Direct	
		Indirect	
		Sum	
	Labor cost	Direct	
		Indirect	
		Sum	
	General cost	Direct	Depreciation
			Test
			Evaluation
			Events
			Outside processing
			Insurance
			Sum
		Indirect	
		Sum	
	Management cost		
	Profit		
	Sum		
Sum			

Figure 24. FFX lead-ship acquisition cost components

Calculations were performed based on the following assumptions:

- Indirect labor cost factor: Sixty percent of direct labor cost
- Indirect general cost factor: Twenty-five percent of direct general cost
- Management cost: Two percent of the manufacturing cost
- Manufacturing cost: Sum of the material, labor and general costs
- Profit: Ten percent of total cost
- Total cost: Sum of the manufacturing and management costs

6. Multi-Objective Design Optimization

The result of the FFX alternatives design synthesis is as shown in Table 6.

Table 6. FFX alternatives design synthesis result

Alternative	Factors (X)			Responses (Y)				
	Range (X_1)	Payload (X_2)	Margin (X_3)	Displ (lton)	Seakeeping (McC)	Speed (kts)	Cost ($M)	OMOE
A1	M	M	H	5108	11.153	31.5	534.8	0.696
A2	M	H	M	5342	11.903	31.5	569.9	0.773
A3	M	M	M	4669	9.708	31.6	504.4	0.693
A4	L	M	M	4328	8.537	31.7	491.7	0.666
A5	M	M	L	4270	8.329	31.7	476.7	0.685
A6	L	H	H	5457	12.267	31.5	589.9	0.753
A7	H	L	L	4355	8.627	31.7	374.8	0.598
A8	M	L	M	4415	8.84	31.6	389.7	0.571
A9	H	M	M	5031	10.905	31.6	517.9	0.723
A10	H	L	H	5215	11.492	31.5	433.4	0.614
A11	H	H	L	5242	11.588	31.5	551.1	0.792
A12	L	H	L	4553	9.318	31.6	526.5	0.73
A13	L	L	L	3752	6.439	31.9	354.3	0.543
A14	L	L	H	4454	8.975	31.6	403.4	0.552
A15	H	H	H	6367	14.98	31.5	628.3	0.822

First, design outputs are transformed in terms of cost and effectiveness. The effectiveness (OMOE) is plotted versus lead-ship acquisition cost as shown in Figures 25

and 26. Through these plots, design optimization can be achieved through maximizing OMOE and minimizing lead-ship acquisition cost.

Figure 25 shows design outputs from a “traditional” method. Alternative ship designs were analyzed using six design variables (beam, depth, endurance, store duration, payload, and design margin). For this analysis, the FFX was synthesized for fifteen alternative options from the designer’s perspective. The slight variation in design variables leads to clumping of solutions. The range of potential solution possibilities does not span the entire cost range of interest.

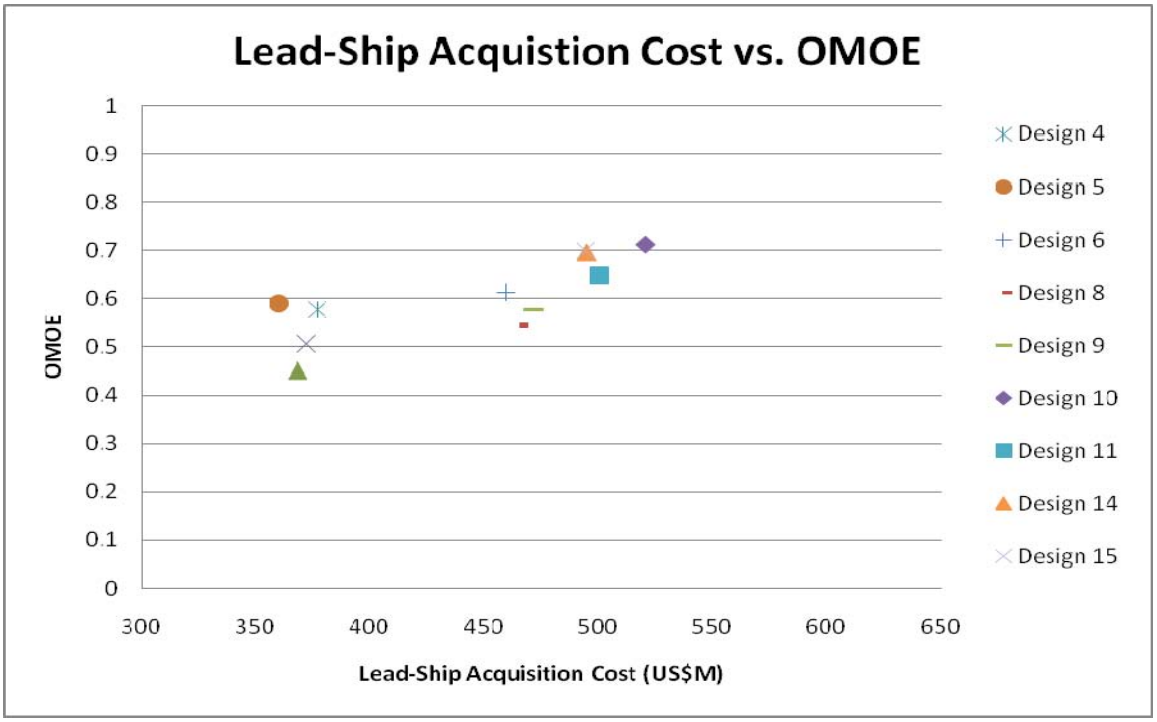

Figure 25. Lead-ship acquisition cost vs. OMOE from traditional method

The DOE method alternatives are plotted in Figure 26, based on Table 6. Ship synthesis was guided by the DOE process in order to create an RSM. As shown in Figure 26, effectiveness (OMOE) tends to be proportional to lead-ship acquisition cost for the FFX. Potential solutions span the entire design space. A high level payload such as designs 2, 6, 11, 12 and 15 leads to high effectiveness and also to high lead-ship acquisition cost. On the other hand, low-level payload such as design 7, 8, 10, 13 and 14 tends to lead to low effectiveness and lead-ship acquisition cost.

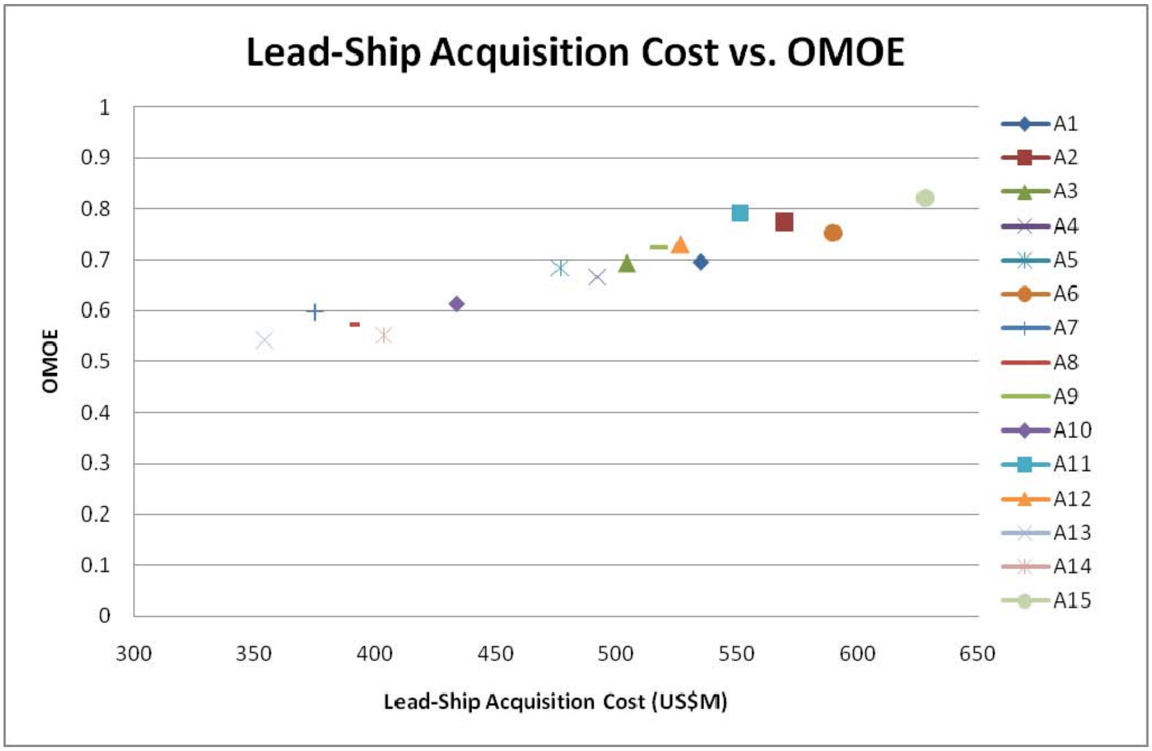

Figure 26. Lead-ship acquisition cost vs. OMOE from DOE process

Designs 7 and 10 have relatively less lead-ship acquisition cost with a low-level combat system payload. Without an effectiveness threshold or goal, it is too difficult to determine whether it is an appropriate design or not. Nevertheless, the value of 0.6 in effectiveness will be too low.

Design 9 has a slightly greater effectiveness with medium level combat system payload. This design has a good endurance range (6,000 nm) and sustained speed (31.6 knots) with 5 percent design margin.

Design 11 has a high effectiveness with high-level combat system payload. If the design is performed with a low cost limitation, design 11 can also be a good choice for the FFX.

Figure 27 shows a comparison between the traditional method and the DOE process. The design outputs from the DOE process tend to span the design space as opposed to the grouping from the traditional method. Design outputs from the traditional method seemed to be intermittent because it depended on the designer's alternatives

selection. The traditional method is not an appropriate way to find an optimal design. Trade-offs are accomplished more completely using the DOE/RSM process.

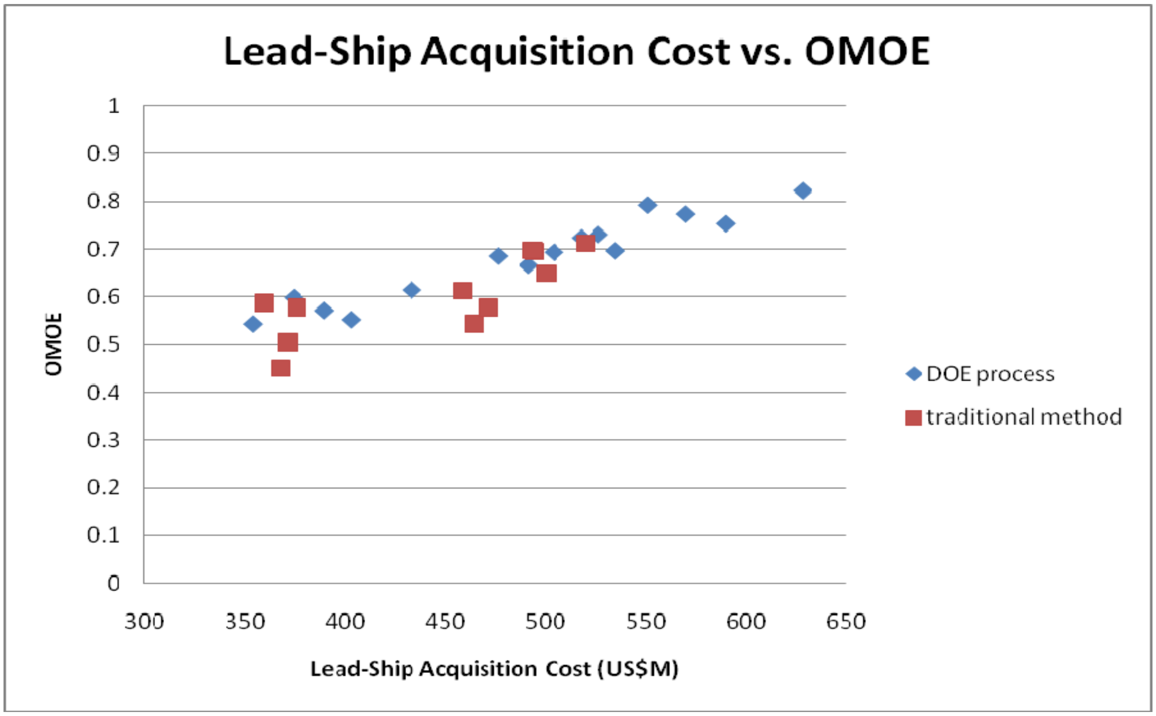

Figure 27. Comparison between traditional method and DOE process

Multi-dimensional trade-offs are accomplished using the JMP software, as shown in Figure 28. This figure shows how design factors (Range, Payload, and Margin) impact the design responses (OMOE, cost, displacement, seakeeping, and speed). The entire design space is displayed for analysis and trade-off. An example feasible design solution space is indicated by the white area of the plot, as constrained by limits on the responses. This area is determined by stakeholder preferences. In this example, OMOE, seakeeping, and speed low limit were fixed at 0.7, 9.5, and 30, respectively, and the cost high limit was fixed at $550 million dollars at an endurance range of 5,500 nm.

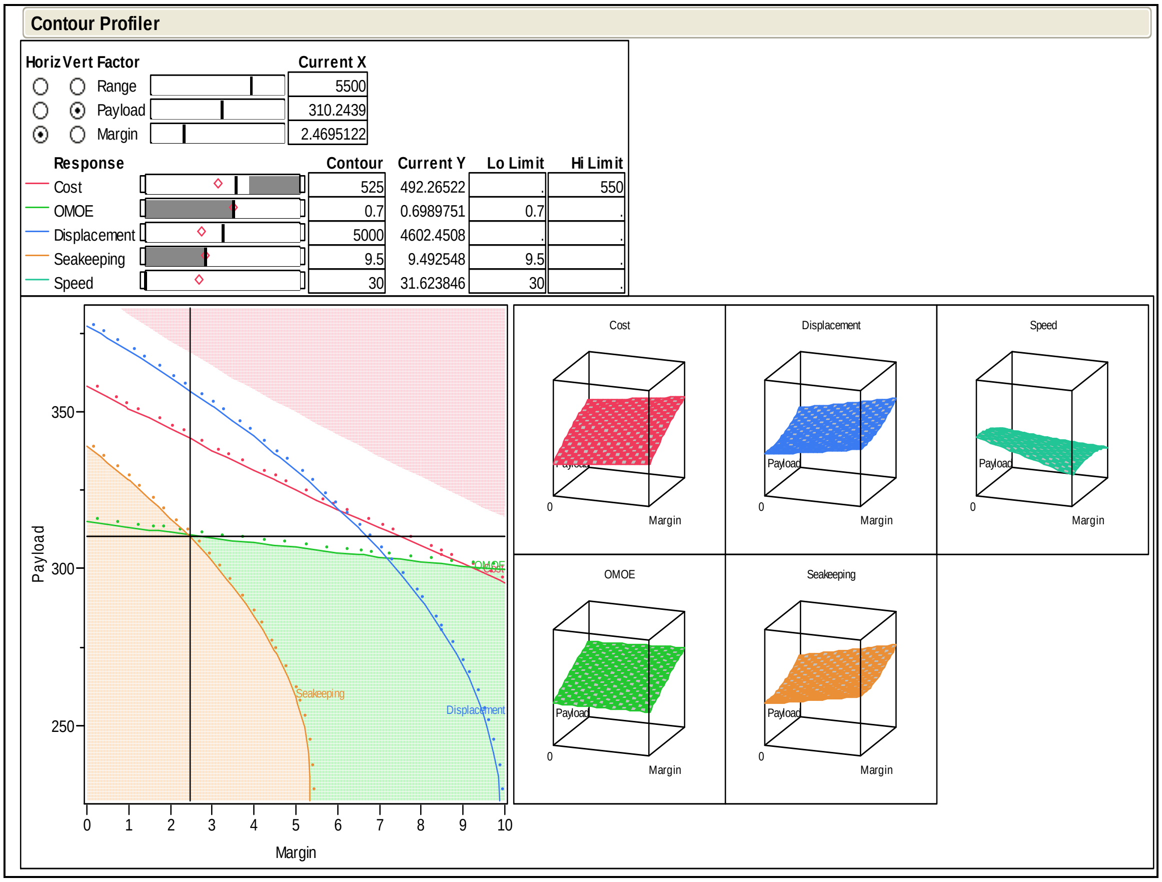

Figure 28. Design space contour plot

With the contour plots, an almost infinite number of design combinations can be traded off. For example, maximum OMOE that can be achieved in this design space is about 0.777. At 0.777 OMOE design point, the FFX is 5140 tons displacement, 11.25 seakeeping, and 31.5 knots speed. Also, minimum cost that can be achieved in this design space is about $492 million dollars. At this design point, the FFX is 0.699 OMOE, 4600 tons displacement, 9.48 seakeeping and 31.6 knots speed.

In order to demonstrate trade-offs more effectively, twelve alternatives within the design space are identified in Figure 29. These alternatives can help decision makers to find optimal design with greater ease.

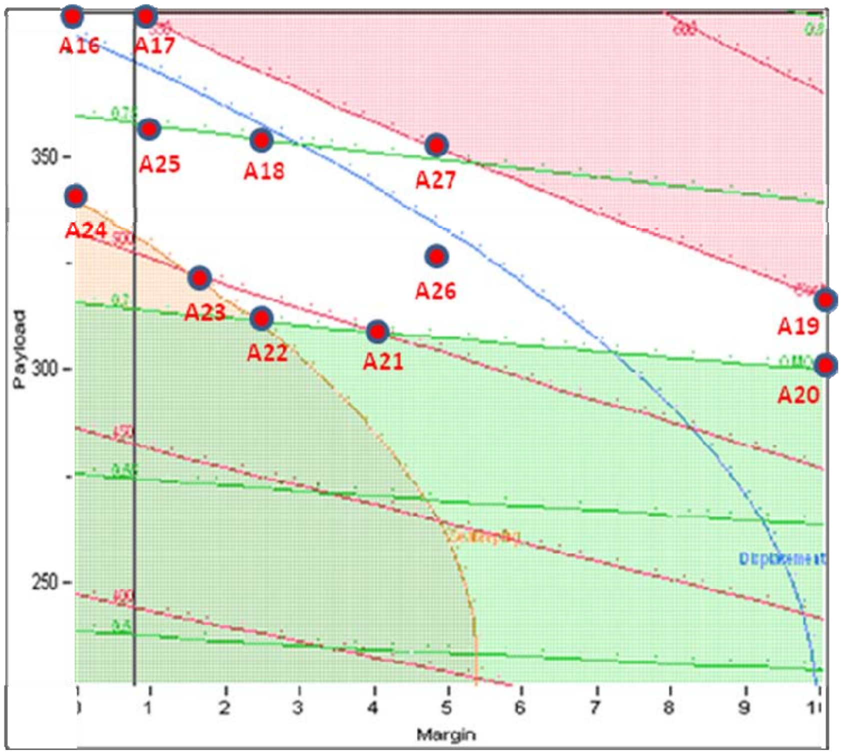

Figure 29. OMOE and cost contour plot

Table 7 shows the value of design variables and its outputs for the alternatives.

Table 7. FFX alternatives within the design space

Alter-natives	Payload (ton)	Margin (%)	Displ (lton)	Seakeeping (McC)	Speed (kts)	Cost ($M)	OMOE
A16	383	0	5062	11.0	31.5	544.7	0.775
A17	383	0.8	5141	11.3	31.5	550	0.777
A18	353	2.4	4956	10.6	31.6	535.8	0.75
A19	317	10	5382	12	31.5	550	0.722
A20	300	10	5259	11.6	31.5	530	0.7
A21	308	4.1	4736	9.9	31.6	500	0.7
A22	311	2.4	4602	9.5	31.6	492.6	0.7
A23	322	1.5	4599	9.5	31.6	500	0.711
A24	339	0	4600	9.5	31.6	507.1	0.727
A25	357	0.8	4839	10.3	31.6	528	0.749
A26	326	5	4953	10.6	31.6	525.7	0.723
A27	350	5	5176	11.3	31.5	550	0.752

Trade-offs are performed among these alternatives using Figures 29 and 30. These show the previous alternatives used for creating the RSM, plus the twelve new alternatives within the design space.

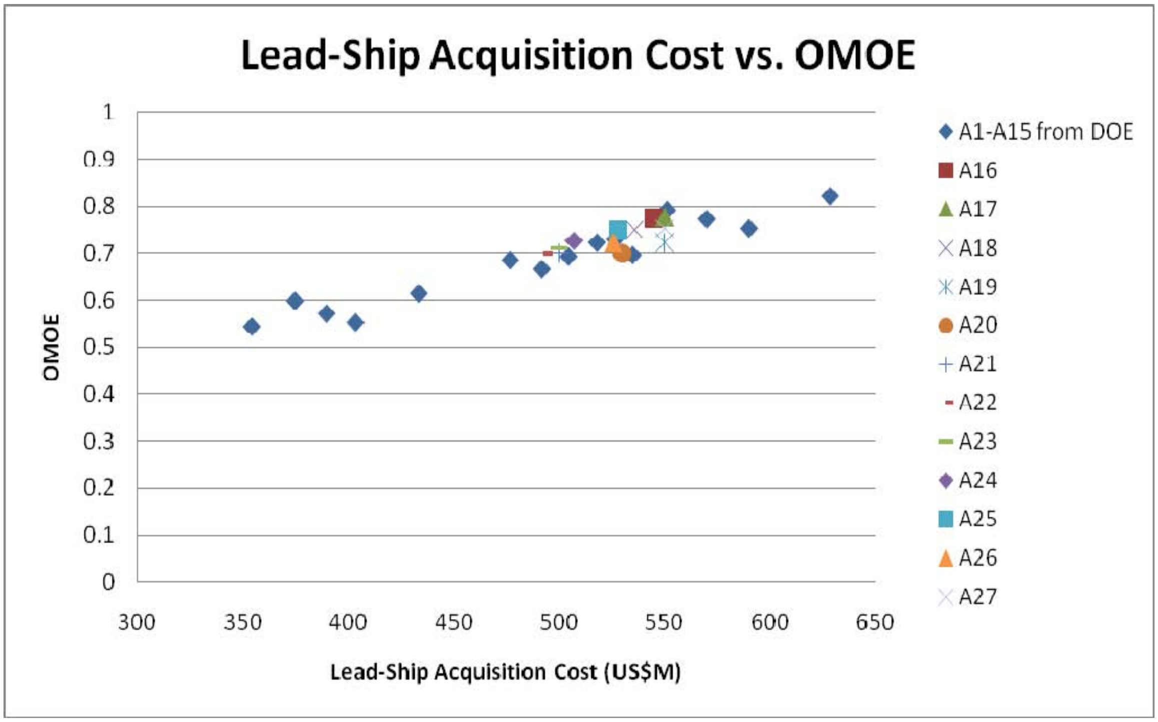

Figure 30. Lead-ship acquisition cost vs. OMOE for new alternatives

The optimal design can be changed, depending on the decision maker's perspective. A17 was chosen as the optimal design due to its possessing the highest effectiveness of 0.777, with an associated cost of $550 million dollars. If the decision makers focus on the effectiveness for the FFX, the design might be considered optimal despite its having a less than 1 percent design margin.

A22 may also be the optimal design when the decision makers focus on the low lead-ship acquisition cost. This ship has an appropriate design margin (2.4 percent), sustained speed (31.6 knots), and OMOE (0.7).

A19 and A20 have the highest design margin (10 percent), but have relatively low effectiveness compared with the other alternatives with the same level of lead-ship acquisition cost. A20, A26, and A27 would not be considered optimal designs for this reason.

The variables and constraints can be varied and re-plotted in real time in JMP to allow interactive trade-offs involving multiple stakeholders.

C. CHAPTER SUMMARY

The new concept design process used in this case study provided a methodology for multi-objective optimization based on effectiveness and cost. This is a rational method used to search a design space non-dominated frontier. The final design must be determined from the stakeholder's preferences from within the design space.

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V. CONCLUSIONS

A. KEY POINTS AND CONCLUSION

1. Why is a Systems Engineering Approach Needed in the R.O.K. Naval Ship Design?

Naval combatant ship design is a complex process. Naval ship engineers should consider not only naval architecture issues such as hull form, stability, structure, maneuverability and propulsion, but also mission needs, effectiveness, cost/risk benefits, and integration with all combat systems.

In the R.O.K. Navy, however, naval ship concept design is still mainly done using a "traditional" naval architecture design spiral method. Naval architects focus only on naval architecture issues such as speed, range, and displacement. However, combat systems engineers focus on the performance of combat systems, weapons, and sensors. This separate design process not only creates some integration problems, but also leads to design changes in the late design stage and during construction. These design problems and the complexity of naval combatant ship design can be controlled by a systems engineering approach.

Systems engineering transforms needed operational capabilities into an integrated system design through concurrent considerations of all life cycle needs. The purpose of implementing a systems engineering approach to complex projects is to design, build, and operate the system with the most cost-effective method in terms of performance, cost, and schedules.

2. How Does the R.O.K. Navy's Concept Design Process Differ from the U.S. Navy's Concept Design Process?

To develop the R.O.K. Navy's systems engineering based applied concept design process, a comparison to the US Navy TSSE program concept design process was performed. The current concept design processes of the two countries' are similar in ship synthesis, but are quite different in some other aspects. The R.O.K. Navy's concept

design process does not include some processes compared with the U.S. Navy's TSSE: Systems Architecture, OMOE model, and Optimization.

The TISNE was developed as part of utilizing the SE approach in the R.O.K. Navy, but it still needs improvement. Through the TISNE, ship synthesis can be achieved. However, the TISNE does not provide for system architecture and optimization process using the cost and effectiveness analysis functions. Moreover, effectiveness analysis has been disregarded in the process of concept design.

On the other hand, in the U.S. Navy's TSSE, the effectiveness model feeds back to the ship synthesis model and creates design optimization in terms of cost effectiveness

3. How Can Systems Engineering be Applied to Naval Ship Concept Design in the R.O.K. Navy?

Based on differences between the two concept design processes as stated above, the newly developed R.O.K. Navy's concept design process is proposed. The main changes of the new concept design process compared to the previous process were system architecture consideration, an OMOE model, and a defined method for performing cost-effectiveness trade-offs.

The constraint associated with developing the new design process will be TISNE. TISNE's development was completed in 2008, as part of a SE approach to the R.O.K.'s naval ship design. This approach assumes that the R.O.K. Navy is willing to continue to use the current system and only improve it if necessary. Therefore, TISNE should be enhanced with overall systems architecture functions along with PMS, KMS, and DES in the Application Layer.

B. RECOMMENDATION

1. Add a Function of Overall Systems Architecture to Current TISNE Version and Develop an OMOE Model Interfaced with TISNE

The new concept design process for the R.O.K. Navy includes the overall systems architecture and OMOE model. It was developed based on an assumption that a function of overall systems architecture should be added to the current TISNE system.

2. Build the Infrastructure for Systems Engineering Implementation in Naval Ship Concept Design

The tools (overall systems architecture, and OMOE/cost model) should be developed first. Second, personnel must be educated in the use those tools, in addition to understanding what systems engineering is and what its processes are. Without enough personnel educated, it will not be possible to implement the systems engineering applied concept design process to the next generation of naval combatant ships.

Personnel education should focus on the officers who are in charge of naval ship design at the Naval Ship Engineering Center (NAVSEC) of the Headquarters of the Navy and at the Defense Acquisition Program Administration (DAPA). Another aspect of education should require that one or two R.O.K. naval officers attend a SE degree or short certificate program every year. It would be helpful to the R.O.K. Navy with respect to updating SE information and trends.

3. Concept Design of Next Generation Naval Ship Using Newly-Proposed Concept Design Process

The R.O.K. Navy has a plan for performing a concept design for the Future Fast Patrol Boat (PKX-B). Therefore, the PKX-B should be designed implementing the new concept design process. As shown in the case study of the FFX, the PKX-B also can be designed in a cost-effective way through the new concept design process.

C. FURTHER RESEARCH

1. Determine the Threshold and Goal of Effectiveness for the R.O.K. Naval Ships

Further studies must refine a way of determining the threshold and goal of effectiveness for the R.O.K. Navy. As shown in the case study, it is hard to determine the metrics for effectiveness. A trade-off study for effectiveness can be performed using both relative and absolute methods. A relative method was presented using AHP. Absolute methods use warfighting M&S to obtain quantitative results, and are generally preferred, whenever possible.

2. Define a Methodology for OMOR in the R.O.K. Navy's Concept Design Process if Necessary

The new concept design process does not include a risk model. However, a naval ship can be optimized using a "Risk" attribute in addition to effectiveness and cost. In this case, an Overall Measure of Risk (OMOR) function is developed to measure the level of overall risk in terms of potential cost, performance, and schedule (Mierzwicki and Brown, 2004). Therefore, a simplified metric and methodology for measuring the risk of the naval ship design must be defined.

APPENDIX A. ASSET MODEL PAYLOAD LIST

Level	Payload & Adjustment Name Table	WT Key
Low	4X MK41 VLS 29-CELL W/29 SM-2	W721
	2X HARPOON SSM TWIN CANNISTER LAUNCHERS	W721
	AN/SWG-1 HARPOON LCH CONT SYS	W482
	HARPOON MISSILES - 4 RDS	WF21
	2X MK32 SVTT ON DECK + MAGAZINE	W750
	1X GOALKEEPER 30MM CIWS [USA/NE]	W710
	GOALKEEPER 30MM CIWS AMMO - 6000 RDS	WF21
	1X MK75 76MM GUN	W710
	MK75 76MM AMMO - 680 RDS	WF21
	1X MK2 WG13 WESTLAND LYNX HELO-MAX	WF23
	LYNX:AVIATION FUEL	WF42
	LYNX:AVIATION FUEL SYSTEM	W542
	LYNX:AVIATION SUPPORT & SPARES	WF26
Medium	8X MK41 VLS 61-CELL W/61 SM-2	W721
	2X HARPOON SSM QUAD HCLS	W720
	AN/SWG-1 HARPOON LNCH CONTROL SYSTEM	W482
	HARPOON MISSILES - 8 RDS	WF21
	2X MK32 SVTT IN HULL WITH MAGAZINE	W751
	1X GOALKEEPER 30MM CIWS [USA/NE]	W710
	GOALKEEPER 30MM CIWS AMMO - 6000 RDS	WF21
	1X MK75 76MM GUN	W710
	MK75 76MM AMMO - 680 RDS	WF21
	1X MK2 WG13 WESTLAND LYNX HELO-MAX	WF23
	LYNX:AVIATION FUEL	WF42
	LYNX:AVIATION FUEL SYSTEM	W542
	LYNX:AVIATION SUPPORT & SPARES	WF26
High	8X MK41 VLS 61-CELL W/61 SM-2	W721
	2X HARPOON SSM QUAD HCLS	W720
	AN/SWG-1 HARPOON LNCH CONTROL SYSTEM	W482
	HARPOON MISSILES - 8 RDS	WF21
	2X MK32 SVTT IN HULL WITH MAGAZINE	W751
	2X GOALKEEPER 30MM CIWS [USA/NE]	W710
	GOALKEEPER 30MM CIWS AMMO - 12000 RDS	WF21
	1X MK45 5IN/54 GUN [HAND SD]	W710
	MK45 5IN AMMO - 600 RDS	WF21
	2X MK2 WG13 WESTLAND LYNX HELO-MAX	WF23
	LYNX:AVIATION FUEL	WF42
	LYNX:AVIATION FUEL SYSTEM	W542
	LYNX:AVIATION SUPPORT & SPARES	WF26

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APPENDIX B. DESIGN SUMMARY OF ALTERNATIVES

Description	Design 1	Design 2	Design 3	Design 4	Design 5
Acquisition Cost (US$M)	534.76756	569.86496	504.35044	491.72029	476.74412
OMOE	0.696	0.773	0.693	0.666	0.685
Lightship Weight (MT)	4108.5	4290.1	3696.2	3525	3322
Displacement (MT)	5108.4	5341.9	4668.8	4327.6	4269.7
LBP (m)	141.5	143.7	137.4	134	133.3
LOA (m)	151.2	153.5	146.8	143.1	142.5
Beam (m)	15.5	15.8	15.1	14.7	14.6
Draft (m)	5	5.1	4.8	4.7	4.7
Depth at ST 10 (m)	10.4	10.6	10.1	9.8	9.8
Cp	0.596	0.596	0.596	0.596	0.596
Cx	0.749	0.749	0.749	0.749	0.749
GMT	1.8	1.8	1.8	1.6	1.7
Seakeeping (McC)	11.153	11.903	9.708	8.537	8.329
Endurance Range (m)	5000	5000	5000	4000	5000
Stored Duration (days)	45	45	45	45	45
Sustained speed (knots)	31.5	31.5	31.6	31.7	31.7
Crew	170	170	170	170	170
Payload (L/M/H)	M	H	M	M	M
Design Margin (%)	10	5	5	5	0

Description	Design 6	Design 7	Design 8	Design 9	Design 10
Acquisition Cost (US$M)	589.87254	374.76003	389.70669	517.88802	433.42531
OMOE	0.753	0.598	0.571	0.723	0.614
Lightship Weight (MT)	4561.3	3271.9	3474.5	3879.7	4067.1
Displacement (MT)	5457.4	4355	4414.9	5030.8	5214.7
LBP (m)	144.7	134.2	134.8	140.8	142.5
LOA (m)	154.6	143.4	144.1	150.5	152.3
Beam (m)	15.9	14.7	14.8	15.5	15.7
Draft (m)	5.1	4.7	4.7	5	5
Depth at ST 10 (m)	10.6	9.9	9.9	10.4	10.5
Cp	0.596	0.596	0.596	0.596	0.596
Cx	0.749	0.749	0.749	0.749	0.749
GMT	1.8	1.7	1.7	1.8	1.9
Seakeeping	12.267	8.627	8.84	10.905	11.492
Endurance Range (nm)	4000	6000	5000	6000	6000
Stored Duration (days)	45	45	45	45	45
Sustained speed (knots)	31.5	31.7	31.6	31.6	31.5
Crew	170	170	170	170	170
Payload (L/M/H)	H	L	L	M	L
Design Margin (%)	10	0	5	5	10

Description	Design 11	Design 12	Design 13	Design 14	Design 15
Acquisition Cost (US$M)	551.07466	526.49309	354.29506	403.42132	628.32367
OMOE	0.792	0.73	0.543	0.552	0.822
Lightship Weight (MT)	4035.4	3702.2	2994.5	3660.4	5082.5
Displacement (MT)	5241.7	4552.9	3752	4453.7	6367.1
LBP (m)	142.8	136.2	127.7	135.2	152.2
LOA (m)	152.6	145.6	136.5	144.5	162.7
Beam (m)	15.7	15	14	14.9	16.7
Draft (m)	5	4.8	4.5	4.8	5.4
Depth at ST 10 (m)	10.5	10	9.4	9.9	9.1
Cp	0.596	0.596	0.596	0.596	0.596
Cx	0.749	0.749	0.749	0.749	0.749
GMT	1.9	1.7	1.5	1.6	2
Sea keeping	11.588	9.318	6.439	8.975	14.98
Endurance Range (m)	6000	4000	4000	4000	6000
Stored Duration (days)	45	45	45	45	45
Sustained speed (knots)	31.5	31.6	31.9	31.6	31.5
Crew	170	170	170	170	170
Payload (L/M/H)	H	H	L	L	H
Design Margin (%)	0	0	0	10	10

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7. LT Hanwool Choi
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